



Land Use Change and Coastal Ecosystem Pressure: A CA-Markov Simulation of Mangrove Dynamics in Brandan Barat, North Sumatra, Indonesia

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Abstract: This study analyzes land-use change dynamics and coastal ecosystem pressure in Brandan Barat Subdistrict, Langkat Regency, North Sumatra, using multitemporal satellite imagery and the CA-Markov spatial simulation model. The novelty of this study lies in the integration of land-use change analysis, ecosystem pressure assessment, and predictive spatial modeling using Landsat imagery (30 m resolution) over a 20-year period (2004–2024), validated with Kappa accuracy, to support ecosystem-based coastal spatial planning. The methods used include multitemporal satellite imagery analysis and spatial analysis to identify the dynamics and trends of land-use change, which are integrated with the CA-Markov model to develop spatial planning scenarios based on predictive modeling. The results show a decrease in mangrove area from 2,282.49 ha in 2004 to 1,292.67 ha in 2014, followed by a slight increase to 1,367.01 ha in 2024, with a total reduction of 915.48 ha during the 2004–2024 period. In contrast, plantation areas increased from 2,792.88 ha in 2004 to 3,748.86 ha in 2014 and 3,775.50 ha in 2024. These conditions increase pressure on protected zones and potentially reduce environmental carrying capacity. Simulation results indicate that controlling land conversion, rehabilitating mangroves, and strengthening spatial planning based on environmental carrying capacity are effective in reducing ecosystem degradation. These findings emphasize the importance of adaptive and ecosystem-based coastal planning that can be replicated in other tropical coastal areas.

Keywords: CA-Markov simulation; Coastal ecosystem; Land use change; Mangroves; Sustainable management

Introduction

Coastal areas are transitional zones between land and sea that possess significant ecological, social, and economic functions. These areas serve as spaces of interaction between human activities and natural systems, making them strategically important for supporting environmental sustainability and the well-being of coastal communities. However, coastal regions are also highly vulnerable to environmental pressures, particularly those resulting from land-use changes driven by human activities.

The western coast of Sumatra, which directly faces the Indian Ocean, experiences the west monsoon season

every year, generating high waves that trigger coastal abrasion. As a result, coastal cities in this region tend to be disaster-prone and may potentially experience the loss of coastal land. In addition, the western coastal areas are characterized by nipa swamp and peatland ecosystems that influence coastal environmental conditions (Wulandari, 2021). In contrast, the eastern coast of Sumatra, which borders the Malacca Strait, is characterized by relatively calmer waters, where sediment deposition processes are more dominant, gradually forming new land areas. This condition has caused several historical coastal settlements that were once located close to the shoreline to gradually move farther inland from the sea. The newly formed land is

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generally composed of mangrove swamp ecosystems that may serve as the initial stage for the development of settlements in river estuary areas (Wulandari, 2021).

Coastal ecosystems such as mangroves play a crucial role in maintaining shoreline stability, reducing coastal erosion, sequestering carbon, and supporting marine biodiversity (Komiyama et al., 2008; Alongi, 2012). Nevertheless, mangrove ecosystems in many tropical coastal regions continue to experience degradation due to land conversion for economic purposes such as plantations, agriculture, and settlement development.

Land-use change is one of the primary factors driving pressure on coastal ecosystems. Increasingly intensive human activities often lead to the transformation of natural land cover into cultivated land or built-up areas. This process can reduce environmental carrying capacity and increase the vulnerability of coastal regions to ecological disturbances such as coastal erosion, tidal flooding, and declining environmental quality (Turner et al., 2007; Lambin & Geist, 2008). In the context of mangrove ecosystems, land conversion not only leads to the loss of natural habitats but also reduces their natural protective functions against coastal hazards (Barbier et al., 2011; Richards & Friess, 2016).

Several previous studies have examined land-use change in coastal areas using remote sensing and Geographic Information Systems (GIS) to identify spatial dynamics and environmental change trends (Weng, 2012; Hasan et al., 2020). In addition, some studies have applied spatial simulation models such as Cellular Automata-Markov (CA-Markov) to predict future land-use changes and support more adaptive spatial planning (Seto et al., 2012; Friess et al., 2019). This approach has proven effective in analyzing temporal land-use dynamics and projecting possible future trends.

However, most previous studies tend to examine land-use change, ecosystem pressure, or spatial simulation separately. Studies that specifically integrate land-use change analysis, ecosystem pressure assessment, and predictive spatial simulation remain relatively limited. Furthermore, the integration of predictive modeling approaches to support ecosystem-based coastal spatial planning is still rarely conducted, particularly in coastal regions of developing countries.

Therefore, a research gap still exists in integrating land-use change dynamics, ecosystem pressure, and predictive spatial simulation within a comprehensive analytical framework. Such an integrative approach is important to provide a more holistic understanding of how land-use changes influence pressures on coastal ecosystems and to support the formulation of sustainable coastal management strategies.

The novelty of this research lies in its integrative framework that simultaneously combines multitemporal land-use change analysis, ecosystem pressure assessment, and predictive spatial simulation using the CA-Markov model within a single analytical workflow. Unlike previous studies that address these components in isolation, this study provides an end-to-end approach—from historical land-cover dynamics to future scenario modeling—specifically applied to a data-scarce tropical coastal subdistrict in North Sumatra. This approach is practically important because it directly informs spatial planning decisions, offering a replicable model for ecosystem-based coastal management in other developing tropical regions facing similar pressures from plantation expansion and coastal land conversion.

This research was conducted in the coastal area of Brandan Barat Subdistrict, Langkat Regency, North Sumatra Province, which has experienced significant land-use changes over the past two decades. The expansion of plantation areas and the increasing extent of built-up areas, accompanied by the decline of mangrove coverage, indicate growing pressure on coastal ecosystems in this region. Therefore, this study aims to analyze the dynamics of land-use change, identify the level of pressure on coastal ecosystems, and simulate future land-use projections using the CA-Markov model as a basis for formulating sustainable coastal management strategies.

Method

Research Location (Geographical and Administrative Location)



Figure 1. Administrative map of Brandan Barat Subdistrict

Brandan Barat Subdistrict is one of the coastal areas located in Langkat Regency, North Sumatra Province. Astronomically, it is located between $04^{\circ}06'16''$ – $03^{\circ}57'18''$ North Latitude and $98^{\circ}18'42''$ – $98^{\circ}11'49''$ East Longitude. The area has an average elevation of approximately 5 meters above sea level, which classifies

it as a lowland area. Brandan Barat Subdistrict covers a total area of approximately 11,070 hectares and is administratively divided into seven villages, namely Tangkahan Durian Village, Sei Tualang Village, Lubuk Kasih Village, Pangkalan Batu Village, Perlis Village, Lubuk Kertang Village, and Kelantan Village.

Data Sources

In this study, the data collection techniques employ a combination of primary and secondary methods to ensure that the data obtained are comprehensive, accurate, and aligned with the research objectives.

Primary Data (Field Observation)

Observation techniques in this study were conducted to address the research problem, namely the pattern of land-use change that influences the level of environmental degradation in the coastal area of Brandan Barat Subdistrict. The observation activities focused on examining the physical environmental conditions, land characteristics, and the impacts of land-use changes on environmental quality. The following table presents the data requirements for field observations used in this study.

Table 1. Data Requirements for Field Observations

Observed Aspect	Indicator	Objective
Land Cover and Land Use Conditions	- Types of land use - Actual field conditions - Land-use conversion (e.g., mangrove converted into ponds or settlements)	To verify the results of satellite image classification (Landsat) and determine the accuracy of land-use change analysis
Coastal Ecosystem Conditions	- Density and health of mangrove vegetation - Coastal water conditions (turbidity, pollution) - Coastal erosion or abrasion - Presence of human activities in the coastal zone	To identify the level of pressure on coastal ecosystems (supporting indicators for mitigation analysis)
Social and Economic Activities of Coastal Communities	- Land utilization for economic activities - Settlement patterns and population density	To understand the relationship between community activities and land-use change and to determine socio-economic criteria in the AHP analysis
Key Location Validation (<i>Ground Check</i>)	- GPS coordinate points - Field condition photographs - Description of actual land use	To conduct spatial validation of the overlay results and the CA-Markov model simulation

Secondary Data

In this study, the required secondary data include documents, books, articles, and archives relevant to sustainable land use for mitigating ecosystem pressure in the coastal area of Brandan Barat Subdistrict, Langkat

Regency. These secondary data are obtained from various related institutions and agencies. The types of secondary data required in this study include the following:

Table 2. Secondary Data Requirements

Data Requirements	Data source
Langkat Regency Spatial Plan Document (RTRW) 2014–2034	Regional Development Planning Agency (BAPPEDA) of Langkat Regency
- Spatial Planning Map (RTRW) of Langkat Regency - Existing land-use data for 2004, 2014, and 2024 - Spatial suitability data and land-use conversion control policies	Public Works and Spatial Planning Office (PUPR) of Langkat Regency
- Indonesian Base Map (RBI) at a scale of 1:50,000 - Administrative boundary, river, and coastline maps - Basic spatial data for land-use change analysis	Geospatial Information Agency (BIG)
- Research data and publications related to land-use change, coastal ecosystems, and CA-Markov simulation - Policy references on ecosystem protection and coastal pressure mitigation	Universities, Ministry of Environment and Forestry (KLHK), and related research institutions

Analysis Techniques

Data analysis in this study was conducted using spatial and descriptive approaches to identify the relationship between land-use change and the level of ecosystem pressure in the study area. The analysis process utilizes multitemporal satellite imagery,

thematic spatial data, and field observation data to support spatial interpretation and land-use policy analysis. The satellite imagery used in this study was obtained from Landsat data accessed through the USGS Earth Explorer platform, including Landsat 5 TM imagery for 2004, Landsat 8 OLI/TIRS imagery for 2014,

and Landsat 8 OLI/TIRS imagery for 2024, all with a spatial resolution of 30 meters. The use of multitemporal data over a 20-year period aims to analyze the temporal dynamics of land-use change in the coastal area of Brandan Barat Subdistrict.

Before the classification process, the imagery underwent a pre-processing stage, which included radiometric correction and atmospheric correction to improve image quality, layer stacking, mosaicking (if required), and clipping based on the study area boundary. In addition, cloud masking was applied to reduce disturbances caused by cloud cover in the imagery. After the pre-processing stage was completed, the imagery was analyzed using land-use classification methods to produce land-use maps for each observation year. The resulting data were then processed using ArcGIS 10.8, TerrSet (CA-Markov), and Microsoft Excel to generate thematic maps, spatial projection simulations of land-use change, and comprehensive quantitative and qualitative analyses.

Land Use Change Analysis (2004–2024)

Land-use change analysis was conducted to identify the patterns and trends of land-use transformation in the coastal area of Brandan Barat Subdistrict during the periods 2004, 2014, and 2024. This

analysis aims to examine the extent to which human activities influence land-cover changes and their relationship with pressures on coastal ecosystems. Through a spatial approach using the overlay method, processed with ArcGIS 10.8 and Google Earth Pro, this analysis focuses on understanding the dynamics of spatial utilization in the coastal area of Langkat Regency. Using this method, it is possible to identify the form, direction, and magnitude of land-use changes over time, thereby providing a comprehensive overview of environmental pressures and spatial structure transformations occurring in the coastal region.

Land Use Classification

The next stage involves performing land-use classification for each satellite image based on the land-use categories present in the study area. The classification was conducted visually by referring to land-cover characteristics such as mangrove areas, plantation areas, vegetation areas, water bodies, and built-up areas. The classification results were then adjusted to actual field conditions through visual interpretation and cross-checking with thematic data and field observation results. The following table presents the land-cover classification used in this study:

Table 3. Land Use Classification Categories

Land Use Classification	Description
Mangrove	Coastal vegetation areas that grow in tidal zones and river estuaries.
Plantation	Cultivated land used for plantation crops such as oil palm and other commodities.
Non-Plantation Vegetation	Natural or semi-natural vegetation areas other than mangroves and plantations, such as shrubs and rice fields.
Water Bodies	Water areas including rivers, estuaries, drainage channels, inundated areas, and ponds.
Built-up Land	Areas that have undergone physical development such as settlements, roads, public facilities, and other infrastructure.
Open Land	Areas without significant vegetation cover, such as bare soil or newly cleared land.

Overlay Analysis

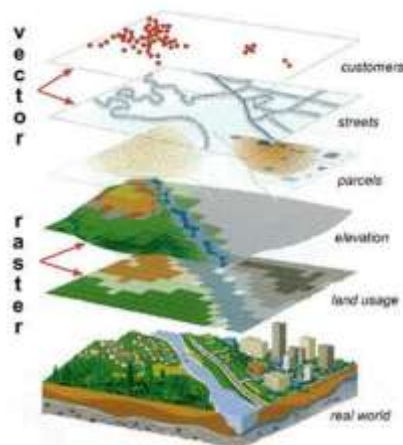


Figure 2. Example of the overlay process scheme (Khusnawati & Kusuma, 2020)

The overlay stage represents the core of the land-use change analysis. In this stage, two land-use maps from different periods (2004–2014 and 2014–2024) were overlaid to identify areas that experienced land-use changes. The overlay results reveal areas that remained unchanged (stable) as well as areas that underwent land-use conversion from one category to another, such as the conversion of mangrove areas into settlements or rice fields into open land.

Land Use Projection Simulation Using the CA-Markov Model

The CA-Markov model was used in this study to simulate and project future land-use changes based on historical land-use dynamics. This model combines the Markov Chain method, which calculates the probability of land-use transitions from one class to another over

time, with the Cellular Automata (CA) approach that incorporates spatial neighborhood interactions in the simulation process. In this study, land-use maps from 2004 and 2014 were used to generate the transition probability matrix, which describes the likelihood of land-use changes between different classes. The transition probabilities were then integrated with spatial driving factors to simulate the spatial distribution of land-use change.

simulation, it is possible to estimate the potential land-use distribution in future periods and identify areas that are likely to experience significant changes. The results of this simulation provide important insights for spatial planning and coastal ecosystem management, particularly in identifying areas vulnerable to land conversion and increasing ecosystem pressure. Therefore, the CA-Markov model serves as a useful tool to support sustainable land management and ecosystem-based coastal planning.

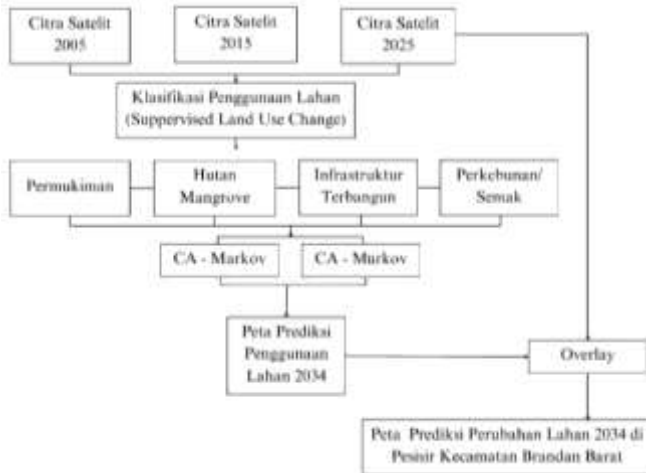


Figure 3. CA-markov modeling framework for land-use change prediction in 2034

The CA-Markov simulation was performed using TerrSet software, which allows spatial modeling of land-use dynamics and future projections. Through this

Kappa Accuracy Test

In this study, the Kappa test was used to measure the level of agreement between the simulation results of the Cellular Automata-Markov Chain (CA-Markov) model and the actual land-use data in the coastal area of Brandan Barat Subdistrict. This test is important to ensure that the simulation model used can be evaluated for its validity before being applied to project land-use changes up to the year 2034.

Table 4. Kappa Accuracy Agreement Categories

Kappa Value (%)	Agreement
< 0	Less than change agreement
0.01-0.20	Slight agreement
0.21-0.40	Fair agreement
0.41-0.60	Moderate agreement
0.61-0.80	Substantial agreement
0.81-0.99	Almost perfect agreement

Research Variables

Table 5. Research Variables, Indicators, and Analysis Techniques

Research Variables	Indicators / Sub-variables	Data Sources	Analysis Techniques	Output
(Land Use Change)	- Land-use classes (mangrove, ponds, settlements, rice fields, shrubs, water bodies) - Area and percentage of changes between years (2004–2014–2024) - Spatial patterns and direction of changes	- Landsat 5 TM imagery (2004), Landsat 8 OLI/TIRS (2014), and Landsat 9 OLI (2024) - RBI maps and administrative maps (BIG, BPS) - Field validation	Image classification Overlay analysis Spatial analysis (ArcGIS/QGIS)	Land-use change map of the coastal area of Brandan Barat Subdistrict

Result and Discussion

Land Use Change from 2004–2024

The assessment of land-use change in Brandan Barat Subdistrict was conducted through a comparative analysis of land-cover areas in 2004, 2014, and 2024. The comparison between these periods aims to identify patterns of change, trends in land conversion, and the dynamics of spatial land utilization that have occurred over the past two decades.

Details of the area of each land cover class are shown in Table 1. Based on the analysis results, Brandan Barat Subdistrict experienced significant land-cover

dynamics during the period 2004–2024. The most notable changes occurred in the mangrove and plantation classes. The mangrove area declined sharply from 2,282.49 ha (25.96%) in 2004 to 1,292.67 ha (14.70%) in 2014, and then slightly increased to 1,367.01 ha (15.55%) in 2024. Overall, the mangrove area decreased by approximately 915.48 ha over the two-decade period. This decline indicates a considerable level of pressure on the coastal ecosystem in the study area.

In contrast, the plantation area shows a significant increasing trend, rising from 2,792.88 ha (31.76%) in 2004 to 3,775.50 ha (42.93%) in 2024. This increase indicates that cultivation activities, particularly plantation

expansion, have become one of the main factors driving land-use change in the coastal area of Brandan Barat Subdistrict. Plantation expansion in the coastal regions of Sumatra, especially oil palm plantations, often occurs through the conversion of natural land such as mangroves and other coastal vegetation due to their

relatively high economic value and the increasing demand for plantation commodities (Richards & Friess, 2016; Austin et al., 2017). This condition suggests that economic pressures and the need to increase community income are among the key factors encouraging land-use conversion in coastal areas.

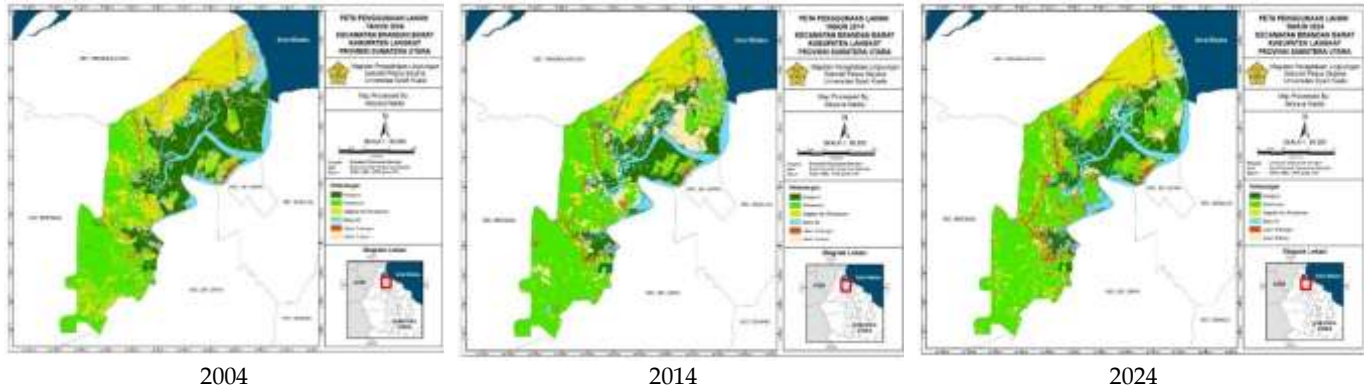


Figure 4. Land use maps of Brandan Barat Subdistrict (2004, 2014, and 2024)

Table 6. Land Cover Area in Brandan Barat Subdistrict (2004, 2014, and 2024)

Land Cover Class	2004		2014		2024	
	Area (Ha)	Presentation	Area (Ha)	Presentation	Area (Ha)	Presentation
Mangrove	2282.49	25.96%	1292.67	14.70%	1367.01	15.55%
Plantation	2792.88	31.76%	3748.86	42.63%	3775.50	42.93%
Non-Plantation Vegetation	1919.97	21.83%	1438.11	16.35%	1563.12	17.78%
Water Body	827.82	9.41%	925.38	10.52%	952.11	10.83%
Built Land	353.88	4.02%	423.72	4.82%	595.89	6.79%
Open Land	616.1	7.01%	964.44	10.97%	539.91	6.14%
Total	8793.18	100%	8793.18	100%	8793.54	100%

In addition to economic factors, infrastructure and settlement development have also contributed to land-use changes in the study area. This is reflected in the increase in built-up land, which expanded from 353.88 ha (4.02%) in 2004 to 595.89 ha (6.79%) in 2024. This growth indicates the expansion of settlements and economic activities, which often follow the development of road networks and community activity centers. This phenomenon is consistent with studies suggesting that infrastructure development and regional accessibility often become major driving factors in the land conversion process in coastal areas (Seto et al., 2012; Hasan et al., 2020).

Changes in the non-plantation vegetation and open land classes also demonstrate relatively complex spatial dynamics. The area of non-plantation vegetation decreased in 2014 and increased again in 2024, although it has not yet returned to its extent in 2004. Meanwhile, open land increased in 2014 but declined again in 2024, indicating that part of this open land was likely converted into plantation areas or built-up land.

The implications of these land-use changes affect not only the spatial structure but also the ecological conditions of coastal areas. The decline in mangrove

areas can reduce the ability of coastal ecosystems to protect shorelines from erosion, decrease carbon storage capacity, and reduce habitats for various coastal species. Mangroves are known to play an important role as buffers for coastal ecosystems, capable of dissipating wave energy, enhancing sediment stability, and maintaining the productivity of coastal waters (Alongi, 2015; Friess et al., 2019). Therefore, the conversion of mangrove areas into cultivated land has the potential to increase the vulnerability of coastal areas to environmental degradation and coastal hazards.

These quantitative findings are also consistent with the results of interviews conducted with respondents in the study area. Several respondents stated that over the past two decades there has been an increase in land clearing for plantation development and coastal economic activities, which indirectly reduced mangrove areas. One informant, Mr. Iwan, stated that *“the conversion of mangrove land into productive land occurred due to economic pressures from local communities and the lack of supervision in the past.”* Another respondent added that although mangrove rehabilitation efforts have recently begun, the ecosystem recovery process requires a long

time and cannot easily restore the original environmental conditions.

In addition to economic and social factors, land-use changes are also influenced by policy and spatial planning management. Limited monitoring of protected coastal areas, combined with opportunities for land utilization for cultivation activities, may encourage the conversion of mangrove areas into other land uses. Therefore, land-use changes in Brandan Barat Subdistrict do not merely reflect spatial dynamics but also represent the interaction of economic, social, infrastructure, and spatial planning policy factors that have developed at the local level.

Land Cover Accuracy Assessment in Brandan Barat Subdistrict for 2004, 2014, and 2024

The land-cover accuracy assessment in Brandan Barat Subdistrict for the years 2004, 2014, and 2024 was conducted to ensure the reliability of the satellite image classification results. The assessment utilized the historical high-resolution imagery feature in Google Earth Pro 7.3.6.9796 as reference data for comparison. The method applied was stratified random sampling, using 300 sample points generated through the Create Accuracy Assessment Points feature in ArcGIS. These points were then compared with high-resolution imagery to generate a confusion matrix, overall accuracy, and the Kappa coefficient. The results of this accuracy assessment are presented as a verification of

the quality and reliability of the land-use classification conducted in this study.

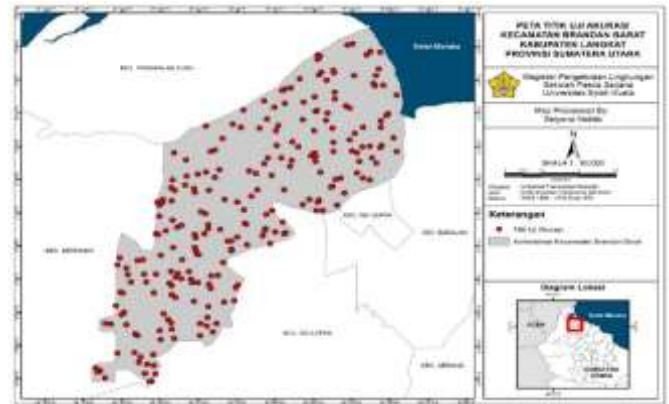


Figure 5. Distribution of accuracy assessment points for land-use classification in Brandan Barat Subdistrict

The land-use accuracy assessment in Brandan Barat Subdistrict for the years 2004, 2014, and 2024 was conducted to ensure the precision and reliability of the image classification results through comparison with reference data. This evaluation employed four main parameters: User Accuracy, Producer Accuracy, Overall Accuracy, and Kappa Accuracy, which collectively provide a comprehensive overview of the classification accuracy, the representativeness of each class, and the consistency of the classification results. The detailed accuracy values are presented in the following table.

Table 7. Accuracy Assessment of Land Use Classification in Brandan Barat Subdistrict (2004)

Land Use Class	Mangrove	Plantation	Non-Plantation Vegetation	Water Body	Built-up Land	Open Land	Total (Users)	User Accuracy
Mangrove	61	0	0	0	0	1	62	98.39
Plantation	6	69	1	0	0	0	76	90.79
Non-Plantation Vegetation	1	2	49	0	0	0	52	94.3
Water Body	0	0	0	22	0	1	23	95.65
Open Land	2	1	2	0	5	0	10	50.00
Open Land	0	1	2	1	0	13	17	76.47
Total (Producer)	70	73	54	23	5	15	20	
Producer Accuracy	87.14%	9.52%	90.74%	95.65%	100.00%	86.67%		
Overall Accuracy	91.25%							
Kappa Accuracy	0.89							

Table 8. Accuracy Assessment of Land Use Classification in Brandan Barat Subdistrict (2014)

Land Use Class	Mangrove	Plantation	Non-Plantation Vegetation	Water Body	Built-up Land	Open Land	Total (Users)	User Accuracy
Mangrove	3	0	0	0	0	1	35	97.14%
Plantation	2	93	7	0	0	1	103	90.29%
Non-Plantation Vegetation	0	5	33	0	0	1	39	84.62%
Water Body	0	1	0	24	0	0	25	96.00%
Open Land	1	0	0	0	8	3	12	66.67%
Open Land	0	2	0	0	0	24	26	92.31%
Total (Producer)	37	101	0	24	8	30	240	
Producer Accuracy	91.89%	92.08%	82.50%	100%	100%	80%		
Overall Accuracy	90%							
Kappa Accuracy	0.87							

Table 9. Accuracy Assessment of Land Use Classification in Brandan Barat Subdistrict (2024)

Land Use Class	Mangrove	Plantation	Non-Plantation Vegetation	Water Body	Built-up Land	Open Land	Total (Users)	User Accuracy
Mangrove	36	0	1	0	0	0	37	97.30%
Plantation	5	98	0	0	0	0	103	95.15%
Non-Plantation Vegetation	2	4	37	0	0	0	3	86.05%
Water Body	3	0	0	22	0	1	26	84.62%
Open Land	0	1	0	0	11		16	68.75%
Open Land	1	2	1	0	1	10	15	66.67%
Total (Producer)	47	105	39	22	12	15	240	
Producer Accuracy	76.60%	93.33%	94.87%	100%	91.67%	66.67%		
Overall Accuracy	89.17%							
Kappa Accuracy	0.85							

The results of the accuracy assessment indicate that the level of precision in the land-use classification in Brandan Barat Subdistrict across the three observation years is considered good and acceptable for further analysis. In 2004, the Overall Accuracy reached 91.25% with a Kappa Accuracy value of 0.89, indicating a very strong agreement between the classification results and the reference data. In 2014, the Overall Accuracy was 90% with a Kappa value of 0.87, while in 2024 the Overall Accuracy reached 89.17% with a Kappa value of 0.85. Overall, the Kappa values across the three periods fall within the strong agreement category, indicating that the classification results have high reliability and are suitable for use in land-use change analysis.

In detail, most land-cover classes show high User Accuracy and Producer Accuracy, particularly for the mangrove, plantation, and water body classes, which consistently achieved accuracy levels above 90% in several periods. This indicates that these classes are relatively easy to identify due to their distinct spectral characteristics. However, some classes, such as open land and built-up land, exhibit lower accuracy values compared to other classes, particularly in 2024. This may be caused by spectral similarities with secondary

vegetation or transitional land areas. Despite these variations among classes, the overall results of the accuracy assessment demonstrate that the classification process meets the standard requirements for land-use mapping accuracy and can be used as a reliable basis for spatial dynamics analysis and subsequent land-use simulation.

Discussion

Predicted Land Cover Simulation of Brandan Barat Subdistrict in 2034

The land-cover projection for Brandan Barat Subdistrict in 2034 was carried out using the Cellular Automata–Markov (CA–Markov) method supported by Logistic Regression in the TerrSet (IDRISI) software. This model utilized land-cover maps from 2004, 2014, and 2024, which were classified using the Maximum Likelihood Classification (MLC) method, to develop a transition probability matrix and spatial rules of land-use change. The CA–Markov approach was selected because it integrates probability-based change analysis (Markov Chain) with spatial neighborhood interactions (Cellular Automata), enabling a more realistic modeling of land-use change dynamics.

Table 10. Predicted Land Cover Area of Brandan Barat Subdistrict in 2034

Land Cover Class	2024		2034	
	Area (Ha)	Presentation	Area (Ha)	Presentation
Mangrove	1367.01	15.55%	1260.36	14.33%
Plantation	3775.50	42.93%	3881.88	44.15%
Non-Plantation Vegetation	1563.12	17.78%	1563.12	17.78%
Water Body	952.11	10.83%	952.11	10.83%
Built Land	595.89	6.79%	595.8	6.78%
Open Land	539.91	6.14%	539.91	6.14%
Total	8793.54	100%	8793.11	100%

The simulation results indicate that in 2034 land cover in Brandan Barat Subdistrict will still be dominated by plantation areas, with an area of 3,881.88 ha (44.15%), increasing from 42.93% in 2024. In contrast, the mangrove area is projected to decline from 1,367.01 ha (15.55%) to 1,260.36 ha (14.33%). Meanwhile, non-

plantation vegetation and water bodies are expected to remain relatively stable at 17.78% and 10.83%, respectively, while built-up land and open land remain below 7% of the total area.

Spatially, land-use changes are projected to occur mainly in transitional zones between inland and coastal

areas, particularly in regions adjacent to existing plantation areas. This pattern indicates a tendency for plantation expansion toward areas previously occupied by mangroves or open land, influenced by factors such as regional accessibility, proximity to road networks, and land suitability for cultivation activities. These predicted patterns can be observed in Figure 6: Land Use Prediction Map for 2034 in Brandan Barat Subdistrict.

To ensure the reliability of the model, validation of the CA-Markov model was performed by comparing the simulation results with actual land-use data from previous periods. The validation process was conducted using Kappa accuracy analysis, a commonly used method for evaluating land-use change modeling. The validation results indicate that the model achieved a satisfactory level of accuracy, making it suitable for predicting future land-use change trends.

Overall, the simulation results provide an overview of land-cover change trends up to 2034, which can serve as a basis for formulating sustainable coastal management policies. The projected decline in mangrove areas requires special attention in spatial planning and environmental mitigation strategies, as

mangroves play a crucial role in maintaining shoreline stability, reducing coastal erosion, and sustaining coastal ecosystem balance. Therefore, these projections can support the development of mangrove protection policies and the control of coastal land conversion in Brandan Barat Subdistrict.

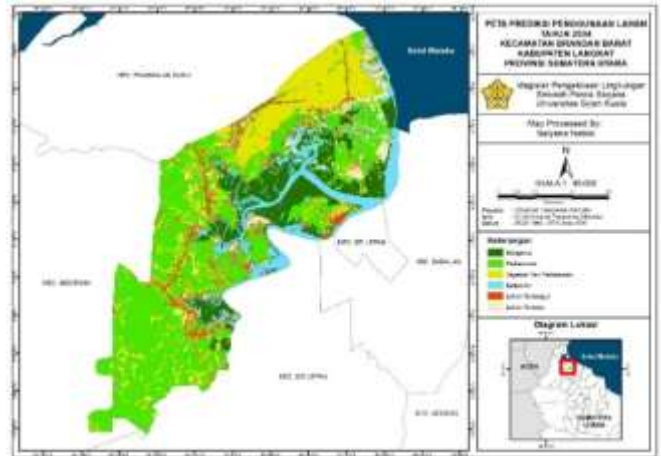


Figure 6. Predicted land-use distribution in Brandan Barat Subdistrict in 2034

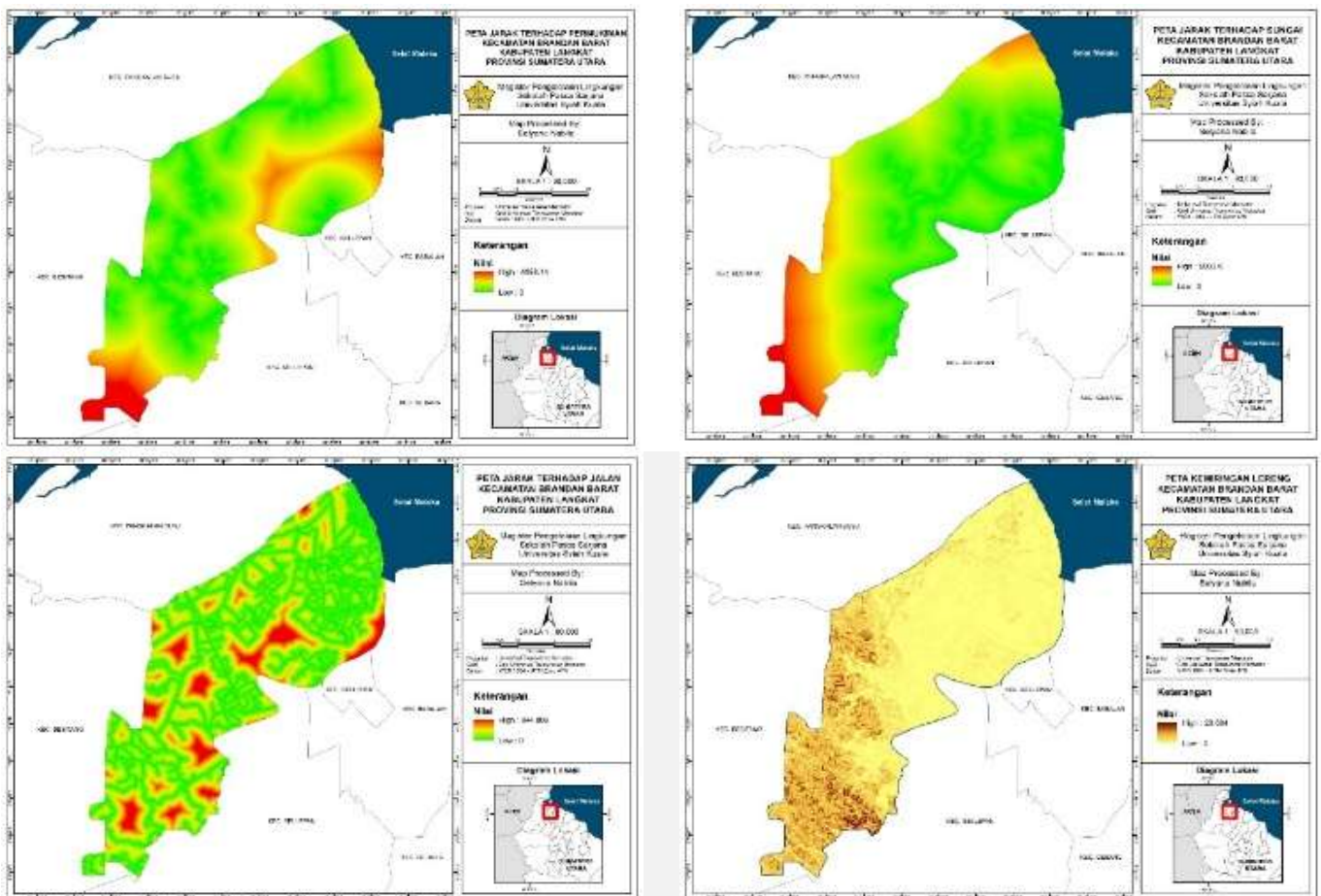


Figure 7. Spatial driving factors used in the CA-Markov model

Driving Factors

Driving factors are spatial variables used to explain the tendency of land-cover change from one class to another. In this study, the factors used include distance to settlements, distance to rivers, distance to roads, and slope, as these variables theoretically influence land-use dynamics in coastal areas experiencing pressure from human activities. These factors were integrated into the Cellular Automata–Markov (CA–Markov) model through a logistic regression approach in the TerrSet (IDRISI) software to generate a land-change probability map. The distance to settlements and roads variables represent the level of accessibility and development potential, as areas located closer to these features generally have a higher likelihood of land conversion. Meanwhile, distance to rivers is related to the utilization of water resources and the spatial distribution of human activities that often develop along river corridors. The slope factor influences land suitability, as areas with flatter slopes are generally more favorable for cultivation and development compared to steeper areas. Therefore, the combination of these factors helps the model predict the direction and spatial distribution of land-cover change more realistically.

Recommendations

Based on the results of the CA–Markov simulation, the recommended direction for sustainable land-use management as an effort to mitigate pressure on the coastal ecosystem in Brandan Barat Subdistrict focuses on mangrove rehabilitation and conservation. The

spatial analysis identified five priority areas that require rehabilitation efforts.

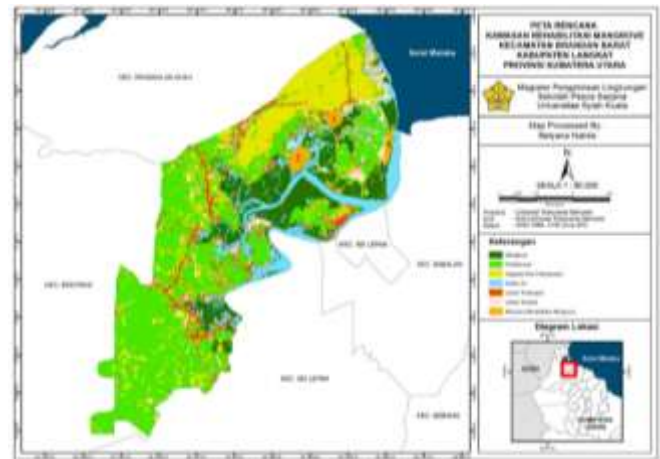


Figure 8. Priority areas for mangrove rehabilitation in Brandan Barat Subdistrict

The first area consists of community settlements located around the river estuary, where most residents depend on coastal ecosystem resources for their livelihoods. The second area is the mangrove tourism site in Lubuk Kertang Village, which has experienced a decline in environmental quality due to illegal mangrove logging and land conversion into oil palm plantations. Therefore, these two areas require rehabilitation and sustainable management efforts to maintain the ecological functions of the coastal environment.



Figure 9. Field conditions of coastal settlements and degraded mangrove areas requiring rehabilitation in Brandan Barat Subdistrict

The third area is a region where the CA–Markov modeling results indicate significant land-use change, particularly the conversion of natural mangroves into oil palm plantations. The fourth area falls within the Indicative Map for the Suspension of New Permit Issuance (PIPPIB), which has a protected status; therefore, land utilization in this area needs to be strictly

controlled. The fifth area is planned for the development of a new coastal ecotourism destination. Consequently, mangrove rehabilitation in these areas is expected to maintain the sustainability of ecological functions while also supporting the development of coastal tourism potential in Brandan Barat Subdistrict.

Conclusion

Land use change in coastal areas driven by human activities has become one of the main factors increasing pressure on coastal ecosystems, particularly mangrove ecosystems. Based on the results of land use change analysis in West Brandan District during the 2004–2024 period, the mangrove area decreased from 2,282.49 ha (25.96%) in 2004 to 1,367.01 ha (15.55%) in 2024, with a total decline of approximately 915.48 ha. In contrast, plantation areas increased from 2,792.88 ha (31.76%) to 3,775.50 ha (42.93%), indicating the dominance of cultivated land expansion and contributing to increasing pressure on coastal ecosystems. The results of the classification accuracy test show a good level of accuracy, with Overall Accuracy values of 91.25% (2004), 90% (2014), and 89.17% (2024), and Kappa Accuracy values of 0.89, 0.87, and 0.85 respectively, which fall into the category of strong agreement. Therefore, the classification results are considered reliable for land use change analysis. The CA–Markov model simulation results indicate that this trend is expected to continue until 2034, where the mangrove area is projected to decline to 1,260.36 ha (14.33%), while plantation areas are projected to increase to 3,881.88 ha (44.15%). The scientific contribution of this study lies in its integrative framework combining historical land-use analysis, Kappa-validated classification, and CA–Markov predictive modeling – a methodological approach that is both replicable and adaptable for other tropical coastal regions facing similar ecosystem pressures. From a policy perspective, the findings support three prioritized recommendations: (1) establishment of mangrove protection zoning within coastal spatial plans to limit conversion in ecologically critical areas; (2) strengthened enforcement of plantation expansion restrictions adjacent to mangrove buffer zones; and (3) development of community-based mangrove rehabilitation programs in the five identified priority areas, particularly in Lubuk Kertang Village and PIPPIB-protected zones. Practically, these results underscore the value of spatial prediction-based planning as a proactive tool for mangrove conservation and sustainable coastal management, with implications for ecosystem service maintenance, carbon sequestration, and coastal resilience in Brandan Barat Subdistrict and comparable tropical coastal areas in Indonesia.

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Author Contributions

Selyana Nabila: Conceptualization, data collection, spatial analysis, writing – original draft. Elysa Wulandari: Supervision, methodology, writing – review and editing. Joni Validation, writing – review and editing.

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Conflict of Interest

The authors declare no conflict of interest.

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