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SPATIOTEMPORAL ANALYSIS OF FOREST LOSS AND LAND USE DYNAMICS IN THE SANGKULIRANG–MANGKALIHAT KARST ECOSYSTEM IN EAST KALIMANTAN

Syaiful Muflichin Purnama*[1], Noor Wahyuningsih[2], Putu Wirabumi[3], Loryena Ayu Karondia[1]

[1]Department of Survey and Mapping, Politeknik Sinar Mas Berau Coal, Berau, Indonesia
[2]Public Policy Researcher, Regional Research and Innovation Agency, East Kalimantan Province, Indonesia
[3]Department of Geography Education, Faculty of Social and Political Sciences, Universitas Negeri Surabaya, Surabaya, Indonesia

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ABSTRACT

The Sangkulirang-Mangkalihat Karst region faces increasing pressure from human activities, particularly Forest Loss, land-use conversion, and industrial expansion, threatening its ecological functions including water storage, biodiversity habitat, and ecosystem services. This study analyzes land use and land cover (LULC) dynamics and Forest Loss patterns in Berau and East Kutai Regencies from 2001 to 2023 using multitemporal remote sensing with Landsat-8 and Sentinel-2 imagery. Land cover classification employed Random Forest algorithm, achieving 90% spatial accuracy. Results reveal complex Forest Loss trends, with highest forest loss in Berau Regency while East Kutai shows fluctuating dynamics. Vegetation recovery was detected, particularly increased high-density forest cover and decreased open land during 2019–2023. Despite regeneration signs, the karst landscape remains under significant pressure from overlapping mining and plantation concessions. The study emphasizes implementing spatial conservation strategies and strengthening karst protection policies, supported by long-term remote sensing monitoring and machine learning algorithms to sustain the ecosystem.

A. INTRODUCTION

Karst ecosystems are landforms created by intensive dissolution of carbonate rocks, such as limestone and dolomite (Ford and Williams, 2007). Although highly vulnerable and difficult to restore once damaged, these ecosystems play a crucial role in maintaining global environmental balance and providing various benefits to humans. According to the Regulation of the Minister of Energy and Mineral Resources No. 17 of 2012, karst is defined as a landscape formed by the dissolution of water in limestone and/or dolomite, whereas Kawasan Bentang Alam Karst (KBAK) refers to areas characterized by distinctive exokarst and endokarst features.

*Correspondence address: sylpurnama@polteksimasberau.ac.id

The Sangkulirang-Mangkalihat Karst Area is one of the largest karst regions in Kalimantan, located in East Kalimantan Province. Based on P3EK Pusat Pengendalian Pembangunan Ekoregion Kalimantan, (2016), the total area covers 3,642,860 hectares, with the widest distribution in Berau Regency and East Kutai Regency, encompassing 2,145,301 hectares or approximately 59% of the total karst area in the province. To date, only the Kawasan Bentang Alam Karst (KBAK) located in East Kutai has been officially designated through a Decree issued by the Minister of Energy and Mineral Resources, whereas the area in Berau remains under proposal.

Karst areas play important roles not only as sources of economically valuable limestone but also as essential water catchment and storage regions for surrounding ecosystems and communities (Sunkar et al., 2022). Additionally, karst contributes to climate change mitigation through its ability to absorb carbon dioxide (CO_2) from the atmosphere. Liu and Zhao, (2000) noted that karst regions can absorb approximately 0.41 billion metric tons of CO_2 annually, although the karstification process releases about 0.3 billion metric tons of CO_2. Thus, the average net absorption remains at 0.11 billion metric tons per year, making karst an important component in the global carbon cycle. Damage to or loss of these areas could potentially accelerate global warming (Cao et al., 2016).

Currently, the Sangkulirang-Mangkalihat Karst faces serious ecological pressure. Data from the (Dinas Lingkungan Hidup Provinsi Kalimantan Timur, 2019) recorded 193 business permits distributed throughout this area, including 110 palm oil plantation permits, 40 forestry concessions, 26 coal mining permits, 16 limestone mining operations, and one cement factory. (Pasapan, 2022) ported that between 2013-2016, more than 60% of the area had been allocated for mining and plantation activities. The cement industry itself contributes significantly to greenhouse gas emissions, with emissions of 22,674.6 Gg CO_2 (Kementerian Lingkungan Hidup, 2014). These findings align with studies by (Gao et al., 2024) showing that land conversion is one of the main factors in karst ecosystem degradation globally.

Karst areas in Berau and East Kutai Regencies experience spatial overlap with mining and plantation operational zones. Data from the East Kalimantan Regional Research Agency shows that East Kutai has seven mining concessions overlapping with karst areas covering 7,612.94 hectares, along with 27 palm oil plantation concessions with overlapping areas reaching 8,844.05 hectares. In Berau Regency, seven mining concessions have conflict areas of 861.84 hectares, and four palm oil plantation concessions overlap with 1,203.96 hectares.

The characteristics of extensive areas, steep terrain, and limited accessibility make traditional monitoring methods suboptimal. Remote sensing offers an effective solution by enabling monitoring of extensive areas without requiring direct physical access to locations (Clements et al., 2014). Machine learning classification techniques, particularly Random Forest, have proven their accuracy in identifying land cover changes using satellite data (Belgiu and Drăguț, 2016). Based on these issues, this research is designed to analyze land use change dynamics in the Sangkulirang-Mangkalihat Karst Area using time-series data from Sentinel-2 and Landsat satellites with Random Forest algorithms.

B. METHOD

Study Area

This research was conducted in the Sangkulirang-Mangkalihat Karst Ecosystem Area (Figure 1) located in Berau and East Kutai Regencies, East Kalimantan Province. This area has been officially designated through the Ministerial Decree of Energy and Mineral Resources (ESDM) No. 140.K/40/MEM/2019, covering a total area of more than 360,000 hectares. In addition to its ecological value, the area holds significant archaeological importance due to the presence of prehistoric cave paintings, which serve as evidence of early human activity (Aubert et al., 2018). With a total area exceeding 360,000 hectares, it is one of the largest karst landscapes in Kalimantan and plays a vital role as an ecological buffer and water source for surrounding communities.

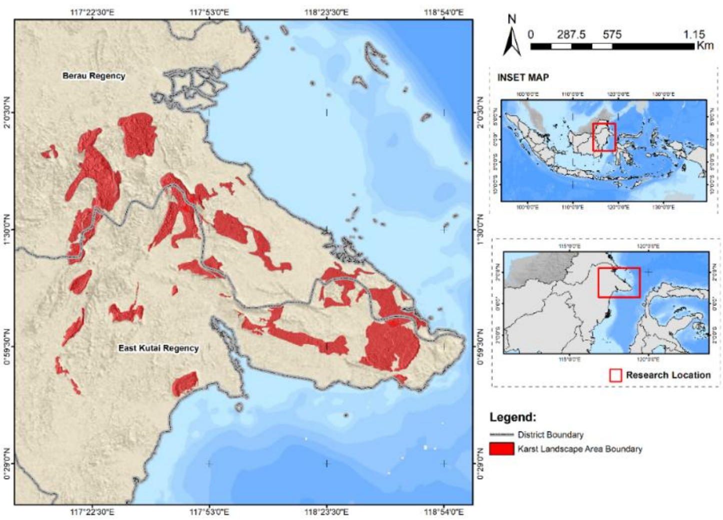


Figure 1. Research location
(Source: Purnama, 2025)

Research Procedure

This study employs a Land Use Land Cover (LULC) change monitoring approach and forest loss analysis utilizing remote sensing technology and cloud-based processing platform, Google Earth Engine (GEE). The primary data used in this research include:

1. Landsat-8: long-term analysis covering the period 2001–2023;
2. Sentinel-2: higher spatial resolution during the period 2019–2023.

The research methodology employed in this study focuses on monitoring Land Use Land Cover (LULC) changes over time in the Sangkulirang-Mangkalihat Karst Ecosystem Area using remote sensing technology. The research workflow is illustrated in Figure 2. The research procedure comprises the following steps:

1. Selection of imagery from Landsat-8 (2001–2023) and Sentinel-2 (2019–2023);
2. Adjustment of image parameters based on data quality and implementation of cloud masking to eliminate cloud-covered pixels;
3. Collection of representative samples from each land cover class as training data;
4. Classification of forest loss into two main classes: forest and non-forest;
5. LULC classification following Indonesian National Standard (SNI) 7645, consisting of four main classes: Dryland Forest (further differentiated into high vegetation and low vegetation); Agricultural Land; and Shrubland/Bushland.
6. Implementation of Random Forest classification algorithm, selected for its capability to handle complex and diverse data, as well as its resistance to overfitting;
7. Accuracy evaluation of classification results using three statistical indicators: confusion matrix, overall accuracy, and kappa coefficient.

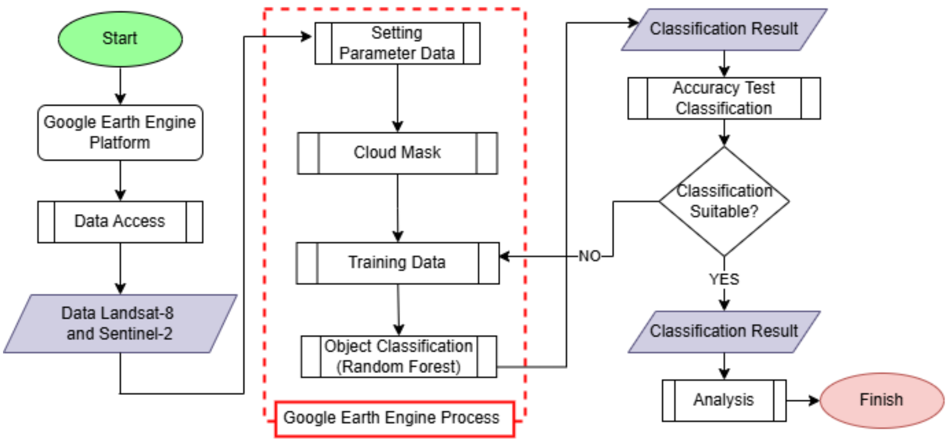


Figure 2. Research Flowchart
(Source: Purnama, 2025)

C. RESULT AND DISCUSSION

C.1. RESULT

The Sangkulirang-Mangkalihat Karst Area plays a strategic role in regional water resource provision due to its unique geological characteristics that facilitate efficient water storage and distribution mechanisms through karst aquifer systems. Nevertheless, this area faces serious threats in the form of environmental degradation triggered by the intensification of anthropogenic activities, particularly those impacting Land Use and Land Cover (LULC) transformation. These transformations include deforestation, expansion of monoculture plantations and mining activities, as well as infrastructure development, which collectively threaten the ecological integrity and sustainability of karst ecosystems.

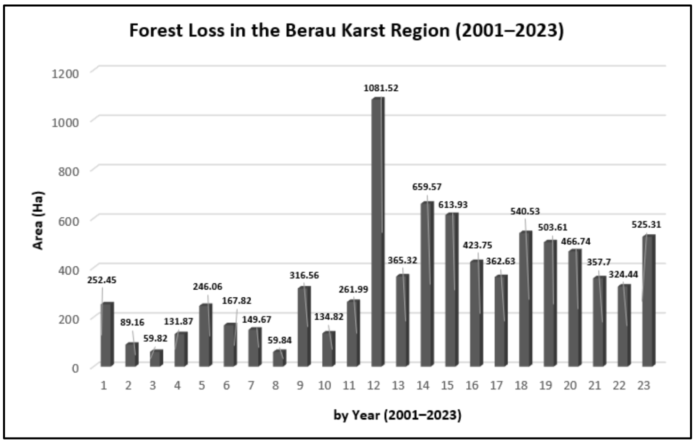


Figure 3. Forest Loss Area Diagram of Berau
(Source: Purnama, 2025)

Spatio-temporal analysis of LULC change dynamics in this area reveals significant deforestation, particularly occurring in the administrative regions of Berau and East Kutai Regencies. The results of deforestation mapping in both regencies, visualized in Figures 3 to 6, display complex forest loss patterns with an overall accuracy level of 90% and a kappa coefficient of 0.8, indicating high reliability of the classification process conducted. To facilitate more systematic analysis and more detailed visualization, the study area was divided into several zones based on their geographical positions. This zonation division comprises Berau Regency consisting of Zones A, B, and C, while East Kutai Regency is divided into Zones A and B.

Research findings indicate that in Berau Regency, Zone C located in the eastern part experienced the most massive forest loss, while in East Kutai Regency, Zone B in the eastern part shows the highest concentration of deforestation, particularly along the karst formation boundary zones. The development pattern of anthropogenic activities tends to follow a gradient from peripheral areas toward the core of the karst region, resulting in forest habitat fragmentation and the formation of spatial discontinuities among forest blocks that were previously intact and ecologically connected.

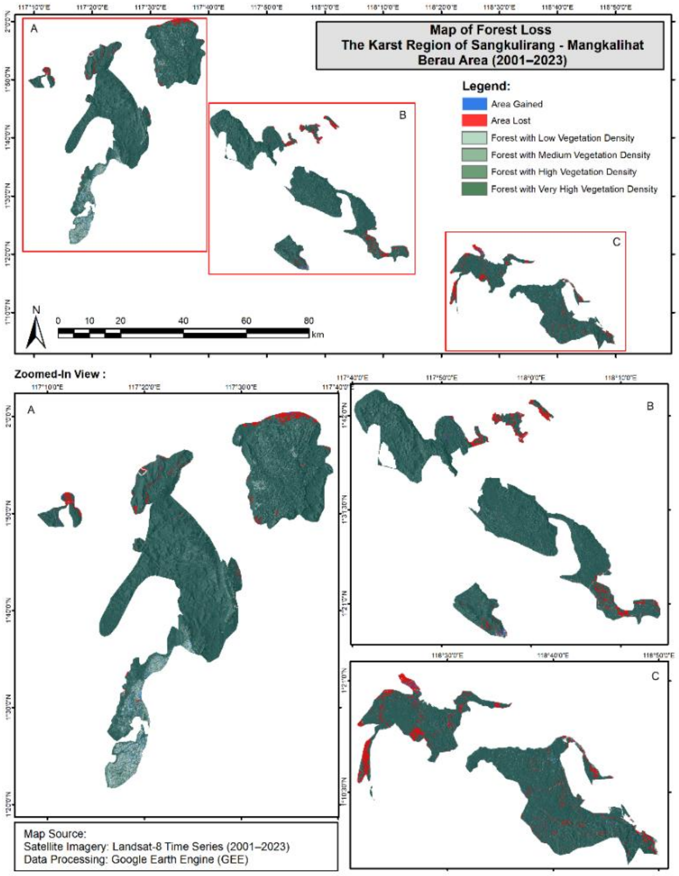


Figure 4. Forest Loss Map of Berau
(Source: Purnama, 2025)

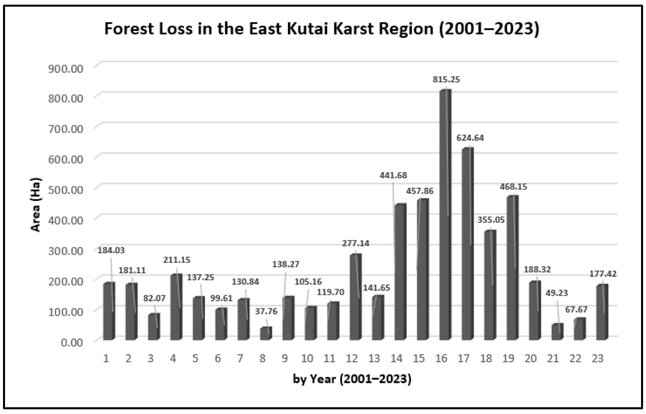


Figure 5. Forest Loss Area Diagram of East Kutai
(Source: Purnama, 2025)

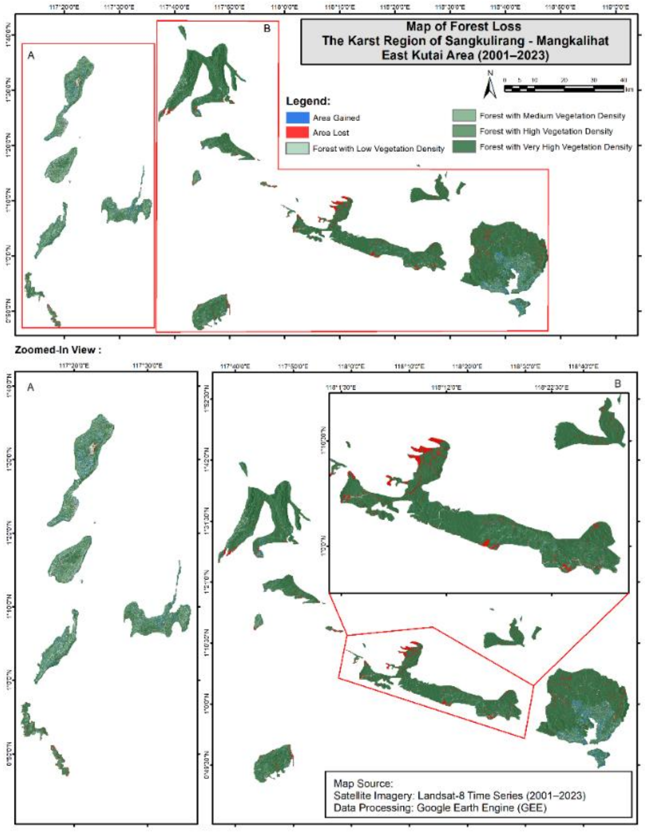


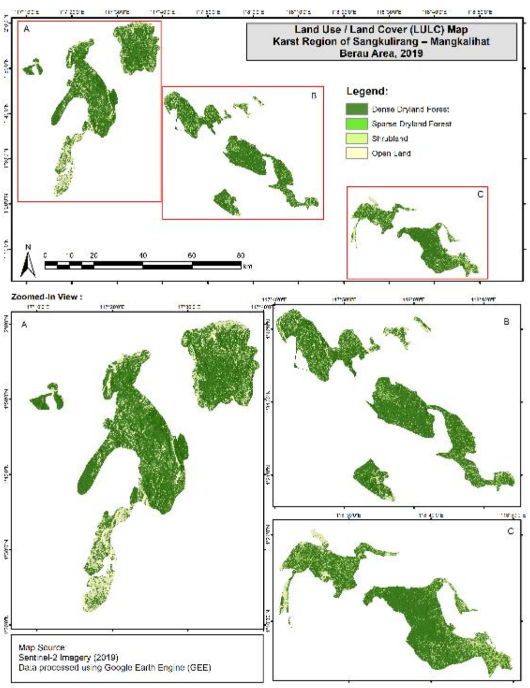
Figure 6. Forest Loss Map of East Kutai
(Source: Purnama, 2025)

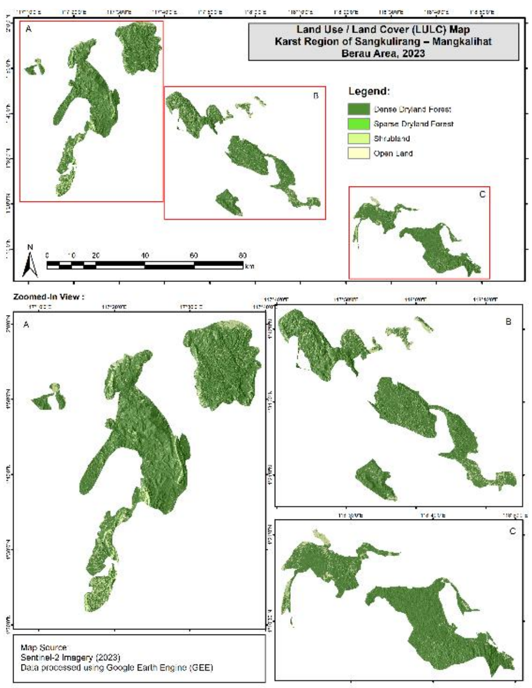
Comparatively, the rate of forest loss in Berau is higher and has persisted longer than in East Kutai, which showed a decline after 2017. However, forest loss trends have increased again since 2021, indicating a risk of ongoing degradation. This condition reflects continuous anthropogenic pressure on the Berau karst system, where forest cover loss can significantly impact karst hydrological functions that possess networks of caves and underground rivers that are highly sensitive to surface vegetation changes.

Furthermore, analysis of LULC changes from 2019 to 2023 based on Sentinel-2 imagery reveals significant dynamics in the Sangkulirang-Mangkalihat Karst Area. This research employed the random forest method for LULC classification, which proved highly effective with a total accuracy of 97% and a Kappa coefficient of 0.95. This exceptionally high accuracy level guarantees the reliability of the analysis results and provides confidence in the research findings, while simultaneously providing a strong foundation for formulating karst area environmental management strategies. The Kappa coefficient value approaching 1.0

indicates that the resulting classification is substantially better than random classification, demonstrating the model's strength in distinguishing various land cover classes that are important for understanding karst ecosystem conditions. These accuracy statistics were systematically calculated through the Google Earth Engine platform, which enables efficient and validated geospatial data processing.

In Berau Regency, the analysis results show complex patterns of change concentrated in specific areas. Although most of the region maintained its land cover during the observation period, significant changes were identified in ecological transition zones. These transition zones represent areas of shift between primary forest ecosystems, shrubland, and open land, which in the karst context function as buffer zones to protect underground hydrological systems and generally serve as early indicators of anthropogenic pressure on karst areas. These change patterns are primarily concentrated in zones A and C, as visually documented in Figures 7 through 9. These zones demonstrate higher ecological vulnerability to human activities and could potentially become starting points for wider environmental degradation if not properly managed. Changes in these transition zones require special attention in conservation planning and sustainable resource management in the Sangkulirang-Mangkalihat karst region, considering their impact on karst structure stability and underground water quality.





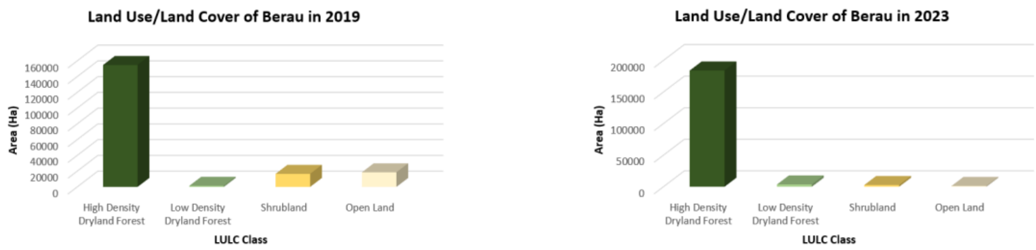


Figure 7. Land Use/Land Cover (LULC) maps and area statistics of the Karst Region in Berau for the years 2019 and 2023
(Source: Purnama, 2025)

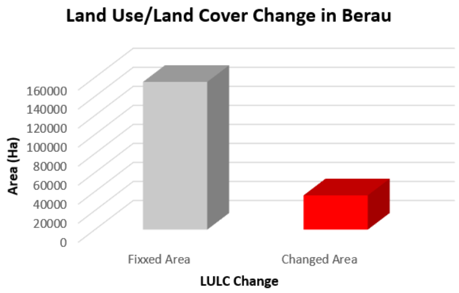


Figure 8. Diagram of LULC Area Changes from 2019 to 2023
(Source: Purnama, 2025)

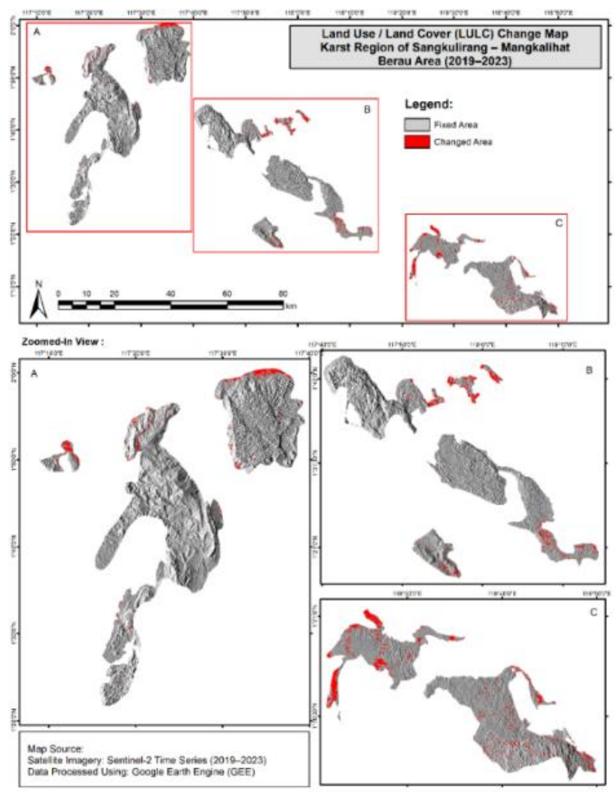


Figure 9. Map of Land Change Areas from 2019 to 2023 in Berau
(Source: Purnama, 2025)

The LULC graph shows that the area of high-density dryland forest increased from around 160,000 hectares to more than 190,000 hectares, while shrubland and open land areas decreased. This condition indicates positive karst ecosystem recovery, where increased high-density forest cover can strengthen karst system hydrological functions by enhancing water infiltration and reducing surface erosion that can damage karst rock structures. This may indicate a natural regeneration process or the success of land rehabilitation programs in the context of karst area environmental management. Similar vegetation recovery patterns have been observed in other karst regions under protection status, where forest restoration initiatives resulted in increased canopy cover and improved ecosystem resilience, ultimately supporting overall karst system stability (Jiang et al., 2014; Wang et al., 2004).

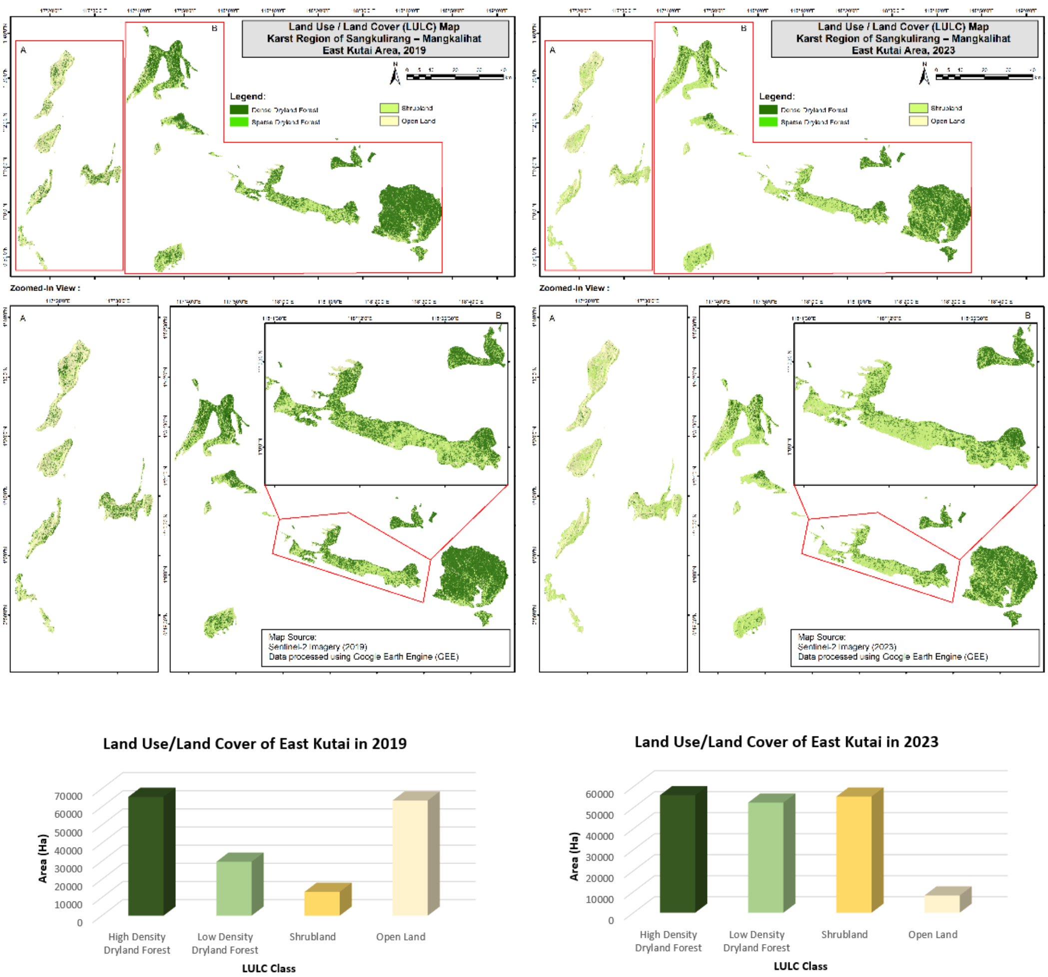


Figure 10. Land Use/Land Cover (LULC) maps and area statistics of the Karst Region in East Kutai for the years 2019 and 2023
(Source: Purnama, 2025)

In East Kutai, significant ecological transformation also occurred with important implications for karst area management. According to Figure 9, the increase in the area of High-Density Lowland Forest from about 45,000 hectares to over 55,000 hectares suggests vegetation recovery that is beneficial for karst systems, although this is accompanied by a dramatic increase in shrubland. The sharp decline in Open Land from around 65,000 hectares in 2019 to less than 10,000 hectares in 2023 reflects successful ecosystem restoration efforts and sustainable forest management, with positive implications for karst hydrological functions by reducing erosion risk and increasing water infiltration. However, Zhang et al., (2016) caution that vegetation recovery in karst regions may mask underlying soil degradation issues that require long-term monitoring, particularly given the sensitivity of karst systems to soil quality changes. The land cover change graph shows that more than 50% of East Kutai's area has undergone changes, indicating a landscape transformation that requires serious attention given the karst region's sensitivity to ecological disturbances, particularly concerning its hydrological functions and karst geological structure stability (Chen et al., 2010).

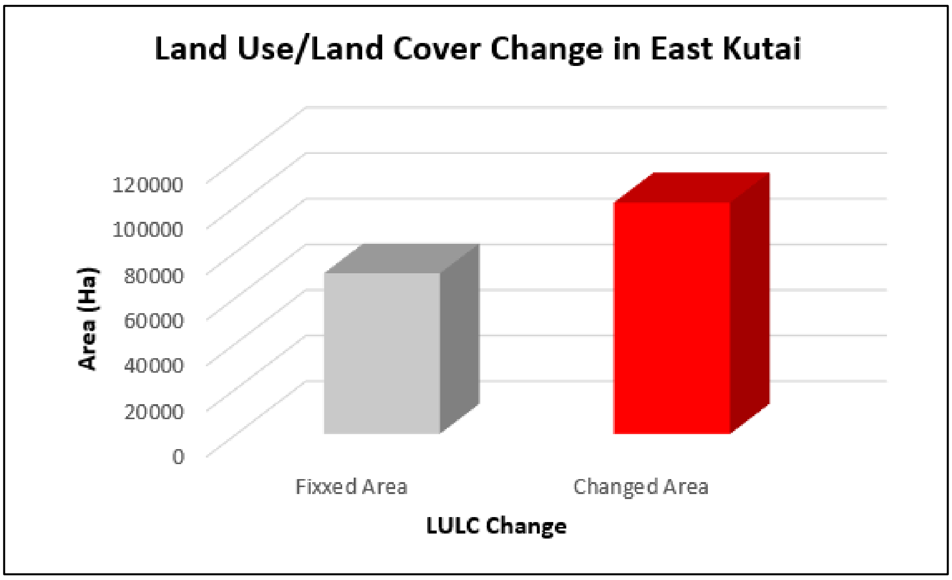


Figure 11. Diagram of LULC Area Changes from 2019 to 2023
(Source: Purnama, 2025)

Several key factors influencing these change patterns in the context of karst area environmental management include the expansion of mining and plantations that can damage karst structures, changes in forest management policies that affect protective vegetation cover of karst systems, land demand pressures from communities and private sectors, and weak law enforcement in protecting sensitive karst areas. According to the implementation of Indonesia's forest moratorium policy has shown varying effectiveness across different regions, with stronger outcomes in areas with clearer land tenure arrangements and robust monitoring systems, which is crucial for karst area management that requires special protection. Budisulistiorini (2022) argues that community-based management approaches could significantly improve conservation outcomes in East Kalimantan's sensitive ecosystems, including karst areas, when supported by appropriate policy frameworks and technical assistance that considers the unique characteristics of karst systems in their management strategies.

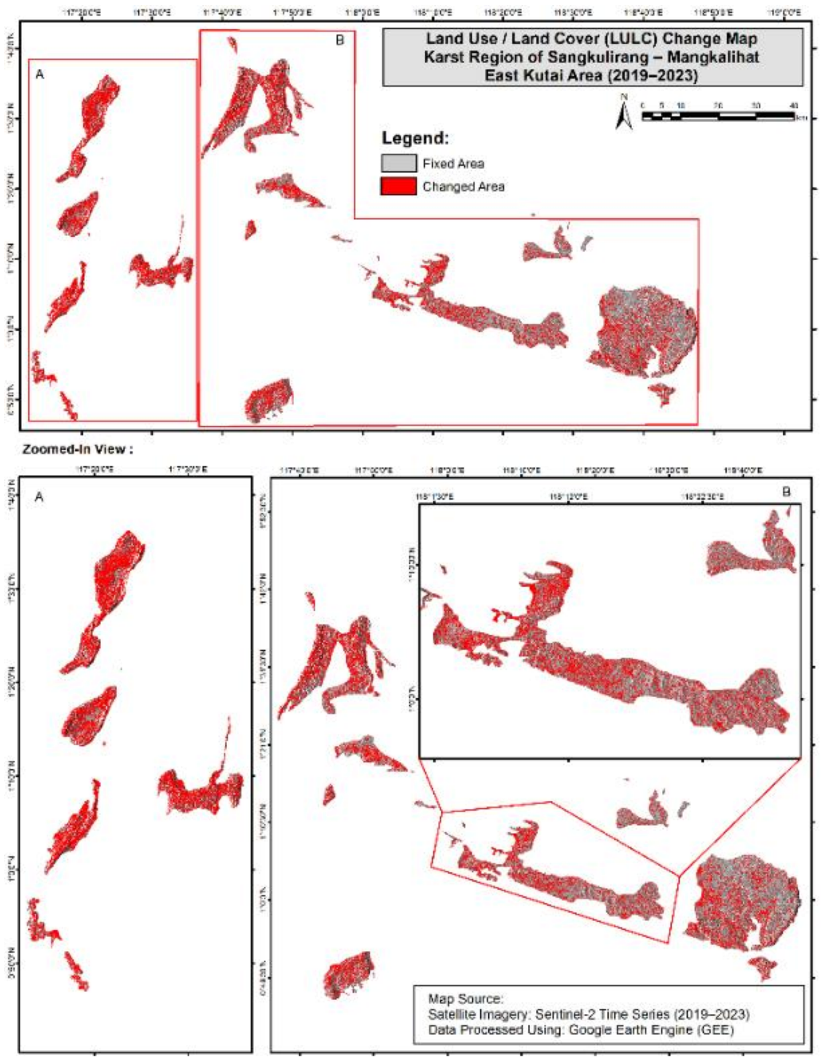


Figure 12. Map of Land Change Areas from 2019 to 2023 in East Kutai
(Source: Purnama, 2025)

The impacts not only cause the loss of forest cover but also threaten critical ecological functions such as carbon storage, hydrological regulation, and the preservation of underground ecosystems. As documented by Goldscheider et al., (2020), karst systems are particularly vulnerable to land-use changes because their unique hydrogeological characteristics enable rapid transmission of surface pollutants to groundwater. Song et al., (2024) further emphasize that karst ecosystems have significantly lower resilience to anthropogenic disturbances compared to non-karst regions, with recovery times often exceeding several decades. Therefore, conservation strategies need to be strengthened through restrictions on business permits within the karst area, strict supervision of extractive activities, and accelerated programs for restoring degraded land.

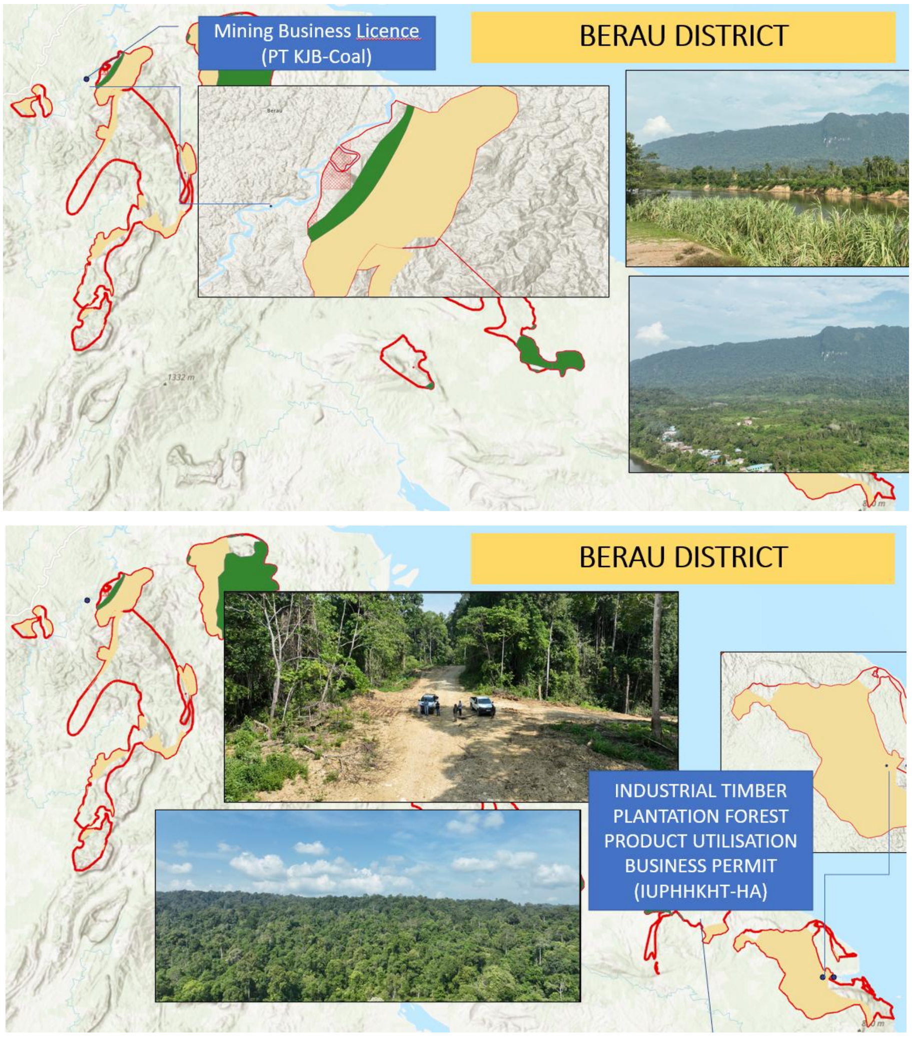


Figure 14. Business Licences that occur in the Berau Karst area
(Source: Purnama, 2025)

According to data from the Research and Development Agency (Balitbangda) of East Kalimantan Province, several locations within the karst area already have Plantation and Mining Business Permits. Figure 12 illustrates the actual distribution of these permits in East Kutai Regency. At the top of the map, the plantation concession area owned by PT AE is visible, characterized by dense vegetation and hilly terrain typical of intensive agricultural landscapes. Meanwhile, the lower part of the map shows the limestone mining concession by PT BL_Limestone, marked by open topography and bare soil, indicating active mining operations.

In Berau Regency, land use dynamics are also evident in Figure 13. The first map shows the coal mining concession by PT KJB-Coal, with hilly landscapes and rivers running through the concession area. The second map presents the industrial timber plantation concession (IUPHHKHT-HA), managed for industrial wood production. Supporting photos depict active forestry operations, dirt roads opened within the forest, and still-dense forest areas, reflecting efforts toward more sustainable management.

Both regencies, Berau and East Kutai, illustrate the complexity of managing a karst region rich in natural resources yet facing significant challenges in balancing utilization and conservation. An integrated approach is required, combining spatial planning policies, law enforcement, community participation, and spatial monitoring technologies to ensure the sustainability of the Sangkulirang-Mangkalihat karst ecosystem.

C.2. DISCUSSION

The Sangkulirang-Mangkalihat Karst Area in East Kalimantan represents a strategic ecosystem with highly significant ecological, hydrological, and geological values. Karst areas are renowned for their ecological vulnerability and fragility. LULC conversion can exert pressure on these areas and deplete their ecosystems, thus impacting communities that depend on these areas for their livelihoods. Several studies on karst areas in China have demonstrated how land conversion directly affects the ecosystem services they provide (Jiao et al., 2022). LULC changes reduce ecosystem values by billions of dollars, and these changes can also diminish and disrupt the regulatory ecosystem services in karst areas (Hu et al., 2019). The impacts of land conversion encompass both physical and socio-cultural elements (Faisal, 2020). The physical or abiotic impacts of land conversion include increased morphological changes and alterations to hydrological systems in karst areas.

In Berau and East Kutai regencies, Forest Loss patterns show differing dynamics. Although there are signs of recovery in recent years, the threat of Forest Loss remains high. Forest Loss in Berau tends to occur on a large scale, especially in the eastern part of the region, while East Kutai has experienced a faster decline in Forest Loss rates but it still persists in strategic areas near the karst boundaries. This reflects differences in the level of pressure and management effectiveness between the two regions.

The 2019–2023 period recorded significant changes in land cover. An increase in high-density forest cover may indicate successful rehabilitation or natural succession. Conversely, the expansion of shrubland in East Kutai might reflect an unstable transitional phase or ongoing pressures on forest areas. The sharp decline in open land, particularly in East Kutai, highlights positive impacts from conservation and restoration efforts, although their sustainability depends on consistent policies and enforcement.

The overlap between karst areas and plantation and mining permits (see Figures 12 and 13) reveals serious challenges in spatial governance. Uncontrolled land use in karst regions can cause permanent damage to ecological functions, including disruption of groundwater systems, loss of biodiversity, and landscape degradation. Increasing forest fragmentation also threatens ecological connectivity vital for the survival of endemic species and natural ecosystem processes.

Therefore, the management of land use and land cover (LULC) changes plays a crucial role in maintaining the sustainability of karst ecosystems. Synergy between government, private sector, and local communities is essential for integrating conservation principles into development policies and natural resource management in this area. Land conversion or land use and land cover (LULC) changes must be well-managed to a certain extent to ensure environmental sustainability and carrying capacity (Litasari et al., 2022; Pu et al., 2020). All sectors must be harmonized and mutually supportive to optimize benefits for society. At the initial stage, sustainability needs to be implemented through sustainable land use (SLU) practices that operate at two levels: technical and policy (Fleury, 2007).

D. CONCLUSION

The Sangkulirang-Mangkalihat Karst Area has experienced significant ecological pressure due to land use and land cover changes, primarily driven by forest loss, plantation expansion, and mining activities. Berau Regency demonstrated higher and more consistent deforestation rates, while East Kutai showed declining forest loss trends despite continuing substantial landscape transformations. Some areas exhibit signs of natural vegetation recovery through increased high-density forest cover and reduced open land, though the sustainability of this recovery depends heavily on effective conservation policies and environmental management practices.

Given the sensitive nature of karst ecosystems and their vital role in water provision, carbon storage, and biodiversity conservation, sustainable management strategies are essential. These include strengthening regulations and supervision of business permits within the karst area, implementing ecosystem restoration in degraded zones, developing spatial planning policies based on conservation principles, and enhancing community involvement in natural resource management. The implementation of these measures is crucial for maintaining the ecological functions of the Sangkulirang-Mangkalihat Karst Area as an environmental support system that provides essential ecosystem services for the sustainability of both local communities and biodiversity conservation.

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