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Land Cover Change in Riau Province and Its Implications for Carbon Stock and CO_2 Emissions

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ABSTRACT

This study aims to analyze peatland land cover changes in Riau Province during 2012, 2016, 2020, and 2024 and their implications for carbon stock and CO_2 emissions. The study used Landsat 7 ETM+ and Landsat 8 OLI/TIRS satellite imagery processed through supervised classification and multitemporal overlay analysis using ArcGIS. The results indicate that vegetation remained the dominant land cover class but experienced a cumulative decline of 1,393,360 ha, especially during 2016–2020 following the 2015 major fires, while built-up areas increased by 249,357 ha. This vegetation loss significantly affected carbon stocks, with an estimated loss of 418,008,000 tons C or 1,534,089,360 tons CO_2, and the 2016–2020 period contributed most to emissions. These findings confirm that peatland land cover changes are not only spatially significant but also influence carbon dynamics and greenhouse gas emissions. Multitemporal remote sensing analysis proved effective in monitoring land cover changes and estimating carbon emissions, providing a scientific basis for sustainable peatland management and regional climate change mitigation strategies

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I. INTRODUCTION

Land cover change is a key indicator for examining the dynamics of environmental systems and the surface energy balance of the Earth (Safitri, et al., 2022). Physically, alterations in vegetation composition and land cover structure influence surface radiative properties, albedo, heat capacity, and the processes of mass and energy exchange between the land surface and the atmosphere. These changes also have implications for the carbon cycle, as each land cover class possesses distinct characteristics in terms of carbon storage and release. In the context of global climate change, land cover dynamics represent a critical variable contributing to fluctuations in greenhouse gas emissions (Zhang et al., 2022).

Peatlands play a critical role in the global carbon cycle. Peat is formed from the accumulation of partially decomposed organic matter under water-saturated conditions, enabling it to store substantial amounts of carbon for hundreds to thousands of years (Novitra & Kurniawan, 2024). The carbon in peat is not present as free carbon, but is primarily stored in the form of complex organic compounds, such as lignin, cellulose, and humic substances derived from plant residues. These compounds are preserved due to anaerobic conditions that slow down decomposition processes. Indonesia is among the countries with the largest extent of tropical peatlands in the world, and Riau Province represents one of the regions with the most extensive peatland distribution in Sumatra (Yuliani, 2017). Under natural conditions, peatlands function as carbon sinks. However, when subjected to drainage, land conversion, or fire, peatlands transition from carbon sinks to carbon sources due to the oxidation of organic matter and the release of CO_2 into the atmosphere (Harenda et al., 2017; Miettinen et al., 2017).

Over the past decade, peatland dynamics in Riau have been strongly influenced by major fire events, particularly during the 2013–2015 period. Peatland fires not only remove surface biomass but also burn the underlying peat layers, resulting in significant carbon losses (Lukman et al., 2025). These events were followed by strengthened peatland restoration policies, including the establishment of the Peatland Restoration Agency and the implementation of rewetting programs aimed at reducing the risk of recurring fires. Consequently, peatland cover changes in Riau during this period reflect the interaction between ecological disturbances and environmental policy responses (Qodriyatun, 2019).

Several studies have examined land cover change and carbon dynamics in peatland ecosystems. Novarina et al., (2024) analyzed peatland transformation in the Kampar Peninsula, Riau, using Landsat imagery from 1990 to 2020 and demonstrated significant degradation of peat swamp forests due to land-use expansion. Their study emphasized the effectiveness of multitemporal satellite imagery in mapping spatial peatland changes.

Regarding soil carbon, Juliano et al., (2024) showed that peatland conversion in Riau affects peat characteristics and soil carbon stocks depending on the duration of land use. Syarif and Achnopha, (2019) reported that peatland fires significantly reduce subsurface carbon stocks. Similar findings were presented by Septian et al., (2023) in estimating subsurface carbon stocks in Jambi peatlands and by Prayitno et al.,(2013) in oil palm agroecosystems established on peat soils. Additionally, Nusantara et al., (2020) demonstrated that land-use change in West Kalimantan directly influences peat soil carbon dynamics.

These studies collectively indicate that land cover change, fire, and land conversion are closely associated with peat carbon stock dynamics. However, such changes occur temporally and are influenced by fire events as well as policy interventions during specific periods. Therefore, an analysis comparing conditions prior to major fire events, the immediate post-fire phase, and the period following strengthened restoration policies is essential to systematically understand the direction of land cover change and its implications for carbon emissions.

Theoretically, land cover change can be analyzed using multitemporal remote sensing data. Landsat satellite imagery provides medium spatial resolution suitable for mapping land cover classes at a regional scale and enables intertemporal change detection analysis (Latue, 2023; Safitri, et al., 2022). Through image classification processes, the area of each land cover class can be quantitatively calculated. Subsequently, carbon emission estimates can be derived by linking changes in land cover extent with appropriate carbon stock values or emission factors for each land cover class. This approach enables the integration of spatial analysis and carbon estimation within an environmental physics framework.

This study focuses on the years 2012, 2016, 2020, and 2024, representing conditions prior to the major fire events, the post-fire phase, and the period following the implementation of peatland restoration policies. Using Landsat satellite imagery as the primary data source, this research aims to

analyze peatland cover changes in Riau Province and examine their implications for carbon emission estimates. The findings are expected to provide scientifically grounded, remote sensing–based information to support peatland management evaluation and the formulation of sustainable environmental policies in Riau Province.

II. METHOD

2.1 Study Area

The study was conducted in Riau Province, Indonesia, one of the regions with the largest peatland distribution in Sumatra. Riau's peatlands have experienced significant land cover changes over the past decade, particularly due to large-scale fire events and subsequent restoration policies. The province was selected as the study area due to its ecological importance in the global carbon cycle and its history of recurrent peatland disturbances.

2.2 Study Design and Observation Years

This study employed a quantitative, multitemporal remote sensing–based spatial analysis to assess peatland cover changes and to quantify their implications for carbon stock variation and CO_2 emissions. Land cover classifications were compared across four observation years representing key phases of peatland fire dynamics: 2012 (pre-major fire), 2016 (post-2015 fire), 2020, and 2024 (extended post-restoration period).

The analytical workflow included satellite data acquisition, image pre-processing, supervised classification, change detection analysis, and estimation of carbon stock changes and CO_2 emissions.

2.3 Data Sources

The primary data used in this study consisted of Landsat 7 ETM+ and Landsat 8 OLI/TIRS satellite imagery for the years 2012, 2016, 2020, and 2024, obtained from the USGS EarthExplorer platform (https://earthexplorer.usgs.gov/). All imagery was provided in GeoTIFF format with a spatial resolution of 30 × 30 meters and a temporal resolution of 16 days.

Satellite images were selected based on low cloud cover percentages and acquisition during the April–September period to minimize atmospheric interference and improve land surface visibility. Administrative boundary data of Riau Province in shapefile (.shp) format were used to delineate the study area and perform image clipping.

2.4 Image Pre-processing

Pre-processing steps were conducted to ensure data quality and analytical consistency. First, Landsat images were examined to confirm acceptable cloud cover levels and overall image quality. Second, the selected images were clipped according to the administrative boundary of Riau Province to restrict the analysis to the study area. Color composites were generated to enhance visual interpretation. Landsat 7 imagery used the 5-4-3 band combination, while Landsat 8 imagery applied the 6-5-4 band combination for vegetation analysis (Safitri et al., 2023).

2.5 Land Cover Classification and Change Detection

Land cover classification was performed using a supervised classification approach with the Maximum Likelihood algorithm in ArcGIS (Abbas et al., 2020). Training samples were defined using Regions of Interest (ROI) for each land cover class. The classification scheme consisted of four categories: (1) vegetation, (2) built-up areas, (3) water bodies, and (4) cloud cover.

The analysis focused primarily on the vegetation class, as peatland vegetation represents the principal aboveground carbon storage component (Wael et al., 2022). Change detection was conducted using overlay techniques between classified maps for the periods 2012–2016, 2016–2020, and 2020–2024. Transitions from vegetation to non-vegetation classes were identified, and the extent of change was calculated in hectares for each period.

2.6 Estimation of Carbon Stock Changes and CO_2 Emission

Carbon stock changes were calculated using the IPCC (2006):

$$\Delta C = A \times EF \quad (1)$$

where ΔC represents carbon stock change (ton C), A is the area of vegetation loss (ha), and EF is the emission factor (ton C/ha).

An average aboveground carbon stock value of approximately 250–350 ton C/ha for peat swamp forest vegetation was adopted based on empirical studies in Southeast Asia (Hiraishi et al., 2014; Page et al., 2011)

Carbon stock changes were subsequently converted into CO_2 emissions using (IPCC, 2006):

$$Co_2 Emission = \Delta C \times 3.67 \quad (2)$$

The factor 3.67 corresponds to the molecular weight ratio of CO_2 to carbon. This approach enabled the translation of vegetation loss due to fire or land conversion into quantitative CO_2 emission estimates at the provincial scale (Sugiarto et al., 2024).

III. RESULT AND DISCUSSION

3.1 Land Cover Dynamics in Riau Province (2012–2024)

The Landsat image classification results indicate that vegetation remained the dominant land cover class in Riau Province throughout the observation period. A detailed summary of land cover changes is presented in Table 1, while the spatial distribution of changes is illustrated in Figure 1. T he slight variation in total area across years is primarily attributed to differences in cloud cover and image acquisition conditions, particularly the inclusion of cloud-covered areas as a separate class in the classification process.

Table 1 Land Cover Change in Riau Province (2012–2024)

Land Cover Class	Years			
	2012 (ha)	2016 (ha)	2020 (ha)	2024 (ha)
Water Bodies	52,427	28,668	25,674	40,726
Cloud Cover	328,531	316,521	1,391,779	1,546,617
Vegetation	8,445,991	8,436,786	7,345,365	7,052,631
Built-up Areas	111,208	218,536	235,988	360,565
Total Area (ha)	**8,938,157**	**9,000,511**	**8,998,806**	**9,000,539**

In 2012, vegetation covered 8,445,991 ha out of a total classified area of 8,938,157 ha. In 2016, the vegetation area slightly declined to 8,436,786 ha, representing a decrease of 9,205 ha. This relatively minor reduction does not yet indicate substantial spatial transformation. In the post-2015 fire context, this condition may be attributed to early-stage vegetation regeneration or shrub cover, which remained classified as vegetation in the imagery.

However, more pronounced changes occurred during the 2016–2020 period. Vegetation area declined significantly to 7,345,365 ha, representing a reduction of 1,091,421 ha. By 2024, vegetation further decreased to 7,052,631 ha. Cumulatively, vegetation loss during 2012–2024 reached 1,393,360 ha. This decline was accompanied by a notable increase in built-up areas, indicating that part of the vegetation loss was driven by land conversion processes rather than solely by degradation. Therefore, the observed changes reflect a combination of vegetation degradation and land use transformation.

From a land cover change perspective, these dynamics reflect the interaction between fire disturbances and land use pressures. In peatland ecosystems, vegetation loss not only reduces aboveground biomass but also accelerates the degradation of underlying organic peat layers.

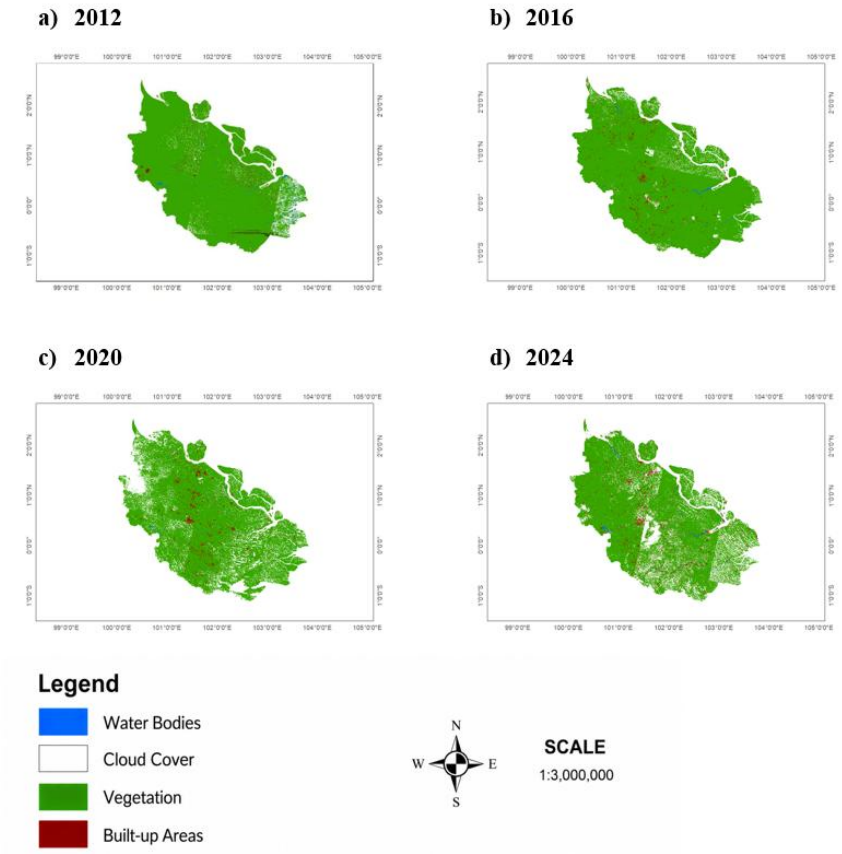


Figure 1 Spatial distribution of land cover changes in Riau Province during 2012–2024

3.2 Expansion of Built-Up Areas and Indications of Land Use Pressure

In contrast to the declining vegetation trend, built-up areas exhibited a consistent increase (Table 1). The extent of built-up land expanded from 111,208 ha in 2012 to 360,565 ha in 2024, representing an increase of 249,357 ha over twelve years.

This growth reflects infrastructure development and expanding economic activities. Spatially (Figure 1), built-up expansion was primarily concentrated around settlement centers and transportation corridors.

Within the framework of land use transition theory, the increase in built-up land represents a more advanced phase of landscape transformation, where economic pressures shift ecological functions toward production or residential purposes. In peatland environments, such transformations are typically permanent due to drainage systems that alter natural hydrological conditions. Consequently, the carbon storage capacity of peatlands declines significantly (Harenda et al., 2017).

3.3 Changes in Carbon Stock and CO_2 Emissions

Vegetation loss during each observation interval was subsequently converted into carbon stock changes and estimated CO_2 emissions. Calculations were conducted using an emission factor of 300 ton C/ha and a conversion factor of 3.67 to convert carbon (C) into carbon dioxide (CO_2).

The summary of vegetation loss, carbon stock changes, and estimated CO_2 emissions for each period is presented in Table 2.

Table 2 Carbon Stock Changes and CO_2 Emissions from Vegetation Loss

Period	Vegetation Loss Area (ha)	Carbon Emissions (ton C)	CO_2 Emissions (ton CO_2)
2012–2016	9,205	2,761,500	10,134,705
2016–2020	1,091,421	327,426,300	1,201,654,521

2020–2024	292,734	87,820,200	322,300,134
Total 2012–2024	**1,393,360**	**418,008,000**	**1,534,089,360**

Overall, the 2016–2020 period contributed the largest carbon loss and CO_2 emissions compared to other intervals. This finding indicates that the impacts of peatland fires and degradation extended beyond the year of occurrence and continued in subsequent years. Such behavior is consistent with peatland ecosystem characteristics, where oxidation processes persist after drainage or hydrological disturbance.

The 2012–2016 period showed relatively minor changes. This suggests that in the early post-fire phase, some affected areas remained classified as vegetation despite potential structural and biomass degradation. During 2020–2024, vegetation loss continued, although at a lower magnitude than in the previous interval.

Cumulatively, carbon stock changes and CO_2 emissions during 2012–2024 demonstrate that peatland land cover dynamics significantly contributed to carbon release into the atmosphere. The magnitude of values shown in Table 2 highlights the direct implications of peatland vegetation change for regional carbon balance and climate systems.

3.4 Discussion from a Theoretical Perspective

The findings indicate that land cover dynamics in Riau Province during 2012–2024 reflect not only spatial changes but also shifts in ecological functions within peatland ecosystems. The vegetation decline identified in Table 1 and the associated carbon emissions in Table 2 align with land cover change theory, which posits that major disturbances can trigger long-term landscape transition phases.

In tropical peatland ecosystems, disturbances such as fire and drainage extend beyond surface vegetation loss. They disrupt hydrological equilibrium, lower groundwater levels, and intensify aerobic decomposition of organic matter. Within the carbon cycle framework, this condition results in carbon emissions originating not only from aboveground biomass but also from decomposing peat layers (Narendra et al., 2023).

The 2016–2020 period, which exhibited the highest emission contribution (Table 2), reflects a lag effect phenomenon in peatland ecosystems. Carbon emissions remain elevated for several years following major fire events because peat decomposition and land subsidence occur gradually. Thus, disturbance impacts are cumulative and do not cease in the year of fire occurrence.

Furthermore, the continuous expansion of built-up areas (Table 1), including settlements, infrastructure, and other forms of land development, indicates that part of the vegetation loss is permanent. From a global carbon cycle perspective, conversion to built-up land represents a transition from carbon sink to carbon source, as natural vegetation is replaced by land uses with significantly lower carbon storage capacity. This transformation has long-term implications, as peat carbon recovery requires considerably more time than its release (Slamet, 2015).

Overall, the results demonstrate a direct linkage between land cover change, peat carbon dynamics, and regional CO_2 emissions. The substantial emission estimates underline that peatland management is not merely a land use issue but an integral component of climate change mitigation strategies.

IV. CONCLUSION

This study demonstrates that land cover dynamics in Riau Province during 2012–2024 were characterized by a decline in vegetation area and a steady expansion of built-up land. Although vegetation remained the dominant land cover class, it experienced substantial cumulative loss by 2024. The most pronounced changes occurred after the major 2015 fire event and continued in subsequent years. Meanwhile, the increase in built-up land indicates persistent land use pressure with potentially permanent ecological consequences.

Vegetation loss directly affected peatland carbon stocks. Using an emission factor of 300 ton C/ha, the cumulative vegetation loss resulted in significant carbon stock changes, which translated into substantial CO_2 emissions. Inter-period analysis revealed that 2016–2020 was the largest emission-contributing phase, reflecting prolonged post-fire oxidation and peat degradation processes.

In conclusion, peatland land cover changes in Riau Province have both spatial and climatic implications. The multitemporal Landsat-based approach processed using ArcGIS effectively captured consistent change patterns through 2024. These findings provide empirical evidence supporting sustainable peatland management policies and regional climate mitigation efforts.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECNOLOGIES IN THE WRITING PROCESS

GPT was used solely to correct grammatical and typographical errors. The author bears full responsibility for the content and integrity of the publication.

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