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Research Paper

Rate of Land Use Conversion to Mining and Implications for Carbon Stocks

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Abstract

Global warming, driven by escalating atmospheric carbon dioxide CO_2 concentrations, represents a critical threat to global climate stability and exacerbates extreme weather events. Indonesia, particularly East Kalimantan and its capital, Samarinda City, serves as a significant contributor to these emissions due to intensive land-use and land-cover changes (LULCC), primarily characterized by deforestation and the rapid expansion of coal mining. The primary objective of this study is to explicitly quantify the rate of land-use conversion and evaluate its direct implications for terrestrial carbon stocks in Samarinda City over a decadal period from 2014 to 2024. To achieve this, the research utilizes high-resolution Landsat 8 OLI/TIRS satellite imagery processed through Geographic Information Systems (GIS) and Google Earth Engine for temporal change detection. Carbon stocks were quantified using the ICLEI carbon calculator by integrating spatial transition data with biomass-based carbon indices. Key findings reveal a substantial decline in the city's total carbon stock, falling from 1,630,212.52 tons in 2014 to 1,442,812.07 tons in 2024. This depletion is fundamentally linked to a 65.22% expansion of mining areas. The results underscore the urgent need for integrating strategic zoning within the Regional Spatial Plan (RTRW) and adopting advanced carbon mineralization technologies to mitigate further carbon stock loss.

Keywords: Global Warming; Land Use Conversion; Mining Expansion; Carbon Stock.

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1. Introduction

Global warming represents a profound and escalating threat to global climate stability, primarily driven by the increasing concentration of atmospheric carbon dioxide CO_2 (Sim et al., 2022). This phenomenon contributes to severe environmental consequences, including more frequent and intense extreme weather events (Singh et al., 2024). Carbon stock defined as the total carbon stored in terrestrial reservoirs such as vegetation, soil, and peat is intrinsically linked to climate change, as the depletion of these reservoirs directly increases atmospheric CO_2 levels (Stokreef, Sadri, Stokreef, & Ghahreman, 2022). According to the International Energy Agency (2023), global CO_2 emissions continue to rise, with Indonesia identified as a major contributor due to widespread land use and land cover change (LULCC), especially deforestation and peatland degradation (Brasika et al., 2024).

Land use type and shifts in carbon density are key variables in evaluating changes in carbon stocks across ecosystems (Qi et al., 2024; Utami et al., 2024). Existing literature presents varied outcomes depending on management practices; for instance, land conversion may increase soil organic carbon (SOC) in surface layers but often reduces carbon in deeper soil horizons an outcome influenced by restoration age and land management practices (Li et al., 2021; Zaberi & Kusin, 2018; Zheng et al., 2023). In specific contexts, such as the Pampa region of southern Brazil, conversion to plantations and agricultural fields had minimal impact on SOC because soil conservation techniques were implemented (Machado, Johnson, Tornquist, Taborda, & Winck, 2024).

However, the conversion of land for mining activities exerts particularly significant and detrimental impacts on carbon stocks and ecosystem integrity (Onifade et al., 2024). Open-pit mining in ecologically sensitive regions disrupts soil structure, eliminates vegetation, and accelerates carbon loss. This pattern has been documented in the Loess Plateau of China, where mining activities substantially reduced carbon sequestration capacity (Chang et al., 2022; Yang et al., 2019; Zhao et al., 2023). Globally, the mining sector occupies more than 101,583 km², frequently within regions of high biodiversity and carbon storage potential (Maus et al., 2022). Such extensive land transformation highlights the urgent need for land-use planning that effectively integrates ecological protection and climate mitigation.

In Indonesia, which ranks among the top ten global contributors to CO_2 emissions (Kartikasari, Rachmansyah, & Leksono, 2019), the expansion of plantations and mining has significantly increased emissions from LULCC (Brasika et al., 2024; Wahyuni & Suranto, 2021). In East Kalimantan alone, coal mining has converted 12,663.28 hectares of forest, contributing 0.60 million tons of CO_2 equivalent emissions (Kartikasari et al., 2019). Historically, land exploitation across Kalimantan resulted in major terrestrial carbon stock losses, with annual reductions averaging 53 teragrams (Tg) of CO_2 between 2006 and 2010 (Goh & Lee, 2021).

Samarinda, the capital city of East Kalimantan, exemplifies these broader regional dynamics. Over several decades, areas once dominated by dense tropical forests have been extensively transformed into coal mining lands (Goh & Lee, 2021; Kartikasari et al., 2019). While the mining sector contributes significantly to regional revenue, large-scale land conversion has degraded environmental quality and substantially reduced vegetative carbon stocks. Mining areas contain negligible carbon storage due to the absence of biomass, making their rapid expansion directly correlated with carbon stock depletion (Purwanto & Sulha, 2024).

Despite the wealth of existing literature, a synthesis of prior research reveals critical methodological and scale-related gaps. First, most existing studies focus on global, national, or provincial scales, lacking the granular, city-scale analysis required to inform municipal spatial planning (RTRW) (Goh & Lee, 2021;Brasika et al., 2024; Wahyuni & Suranto, 2021). Second, the state-of-the-art discussion in prior research often suffers from methodological limitations, such as the use of coarse spatial resolution and static land-cover assumptions, which fail to capture the dynamic and fine-scale transitions inherent in rapidly changing landscapes. Furthermore, while international research has documented ecological degradation within mining zones (Li et al., 2021; Yang et al., 2019), these studies often treat mining in isolation. There is a notable lack of decadal, spatially explicit assessments in complex urban–mining interface regions, where extractive activities aggressively compete with residential expansion. Consequently, this study aims to bridge these gaps by providing a high-resolution, decadal quantification of how rapid mining expansion alters localized carbon stocks in the heterogeneous context of Samarinda City.

2. Methods

2.1. Research Design and Data Sources

This study employs a temporal modeling approach integrating Remote Sensing and GIS. The primary data source consists of Landsat 8 satellite imagery from 2014 and 2024 to ensure consistent spatial resolution for detecting land-cover transitions. This design is specifically structured to capture the trajectory of land-use change, providing a quantitative basis for assessing how shifts from high-biomass ecosystems to extractive zones impact regional carbon storage.

2.2. Sampling and Classification

Sampling was conducted using a stratified random sampling method across 23 land use/land cover classes, categorized in accordance with the Ministry of Environment and Forestry (KLHK) classification standards as regulated under KLHK Decree Number 7 of 2015. This method was employed to validate the accuracy of the satellite imagery classification results.

2.3. Research Tools and Materials

Research tools and materials are crucial components of research design, influencing the quality and success of a study. The following tools were used in this study: stationery, including books or paper and pens or pencils. Their function is to serve as a medium for researchers to record important data during observations. Furthermore, a computer and software applications are required for data processing. Data processing was performed using a high-performance computer equipped with:

1. ArcGIS: For spatial overlay, temporal change detection, and mapping.
2. Google Earth Engine: For digital image processing and atmospheric correction.
3. ICLEI Carbon Calculator: For quantifying biomass-based carbon stocks.

In accordance with these analytical foundations, the specific indices for each land-use category are presented below.

Table 1. Carbon Stock Constant Value Based on Land Use Type

Land Cover Class and Code	Carbon Stock Constant (Tons C/Ha)
Primary dryland forest (Hp / 2001)	195.4
Dryland forest secondary / logged area (Hs / 2002)_	169.7
Primary Swamp Forest (Hrp / 2005)	196
Secondary Swamp Forest / Logged Over (Hrs / 20051)	155
Primary Mangrove Forest (Hmp / 2004)	170
Secondary Mangrove Forest / logged area (Hms / 20041)	120
Plantation Forest (Ht / 2006)	64
Plantation / Garden (Pk / 2010)	63
Shrubs (B / 2007)	30
Swamp scrub (Br / 20071)	30
Savanna / Grassland (S / 3000)	4.5
Dryland farming (Pt / 20091)	10
Dry land farming mixed with bushes/gardens Mix (Pc / 20092)	30
Ricefield (Sw / 20093)	2
Fishpond (Tm / 20094)	0
Built-up land (Pm / 2012)	5
Transmigration (Tr / 20122)	10
Open land (T / 2014)	2.5
Mining (Tb / 20141)	0
Body of water (A / 5001)	0
Swamp (Rw / 50011)	0
Cloud (Aw / 2500)	0
Airport / Port (Bdr/Plb / 20121)	0

Source: Directorate General of Forestry, 2015

The analytical framework of this study is designed to bridge the gap between spatial land conversion and its ecological consequences. By linking temporal land-use maps with carbon stock indices, the analysis quantifies the "carbon penalty" of industrial and urban expansion. This approach does not merely map where change occurs, but explicitly demonstrates how the replacement of natural carbon sinks (such as secondary forests and shrubs) with zero-carbon zones (such as open-pit mining) directly drives atmospheric carbon imbalances. Thus, the findings contribute to a deeper understanding of land-use impacts, providing empirical evidence for climate-resilient spatial planning in Samarinda.

3. Results and Discussions

3.1 Results

A. Identification of Land Use Changes in 2014 and 2024

The analysis of land use dynamics in Samarinda City involved a comprehensive identification of changes in land use between 2014 and 2024. This was achieved by classifying the entire study area into 15 distinct types of land use, providing a detailed snapshot of the region's landscape evolution over the decade.

Table 2. Land Use Changes in 2014 and 2024

Land Cover Class	Percentage Change 2014-2024
Secondary Dryland Forest (Hs / 2002)	163.42%
Plantation Forest (Ht / 2006)	-43.39%
Shrubs (B / 2007)	-33.20%
Swamp Bush (Br / 20071)	49.66%
Plantation / Garden (Pk / 2010)	19.13%
Built-up Land (Pm / 2012)	1189.16%
Open Land (T / 2014)	163.42%
Secondary Mangrove Forest (Hms / 20041)	-
Secondary Swamp Forest (Hrs / 20051)	-99.90%
Dryland Farming (Pt / 20091)	-
Mixed Dryland Farming (Pt / 20092)	-31.28%
Ricefield (Sw / 20093)	7.99%
Harbor (Bdr / Plb / 20121)	-6.01%
Airport (Bdr / Plb / 20121)	0.00%
Transmigration (Tr / 20122)	-
Mining (Tb / 20141)	65.22%
Water Body (A / 5001)	-1.74%
Swamp (Rw / 50011)	-7.66%

Source: Analytical Results, 2025

The land cover change analysis from 2014 to 2024 reveals extensive spatial transformation across Samarinda, driven by rapid urban expansion, intensified extractive activities, and ecological shifts. The most substantial increase is recorded in Built-up Land, which expanded by 1,189.16%. This remarkable growth reflects accelerated urbanization resulting from residential development, the expansion of public and private infrastructure, and the growing concentration of economic activities that have replaced previously vegetated or agricultural areas.

In addition to built-up areas, both Secondary Dryland Forest and Open Land increased by 163.42%. The expansion of secondary dryland forest may indicate natural regeneration processes occurring in previously degraded lands, while the rise in open land is likely associated with clearing activities in preparation for mining, infrastructure development, or other forms of land conversion. These patterns suggest a coexistence of ecological recovery in certain areas and active landscape disturbance in others, illustrating the complexity of land-use dynamics in Samarinda.

Conversely, several vegetated land cover classes experienced significant declines. Plantation Forest decreased by –43.39%, Shrubland by –33.20%, and Mixed Dryland Farming by –31.28%. These reductions highlight strong land conversion pressures driven by settlement expansion, industrial development, and shifting economic activities. Given that these classes contribute meaningfully to carbon storage, their decline directly affects the city's overall carbon sequestration capacity, thereby influencing regional carbon dynamics.

A particularly concerning finding is the near-complete loss of Secondary Swamp Forest, which declined by –99.90%. This substantial reduction signals severe degradation of wetland ecosystems, which play essential roles in hydrological regulation, biodiversity support, and carbon storage. The disappearance of swamp forests points to the vulnerability of wetland environments to drainage, land conversion, and hydrological alterations, and may exacerbate environmental risks such as flooding and declining water quality.

Meanwhile, the emergence of new land cover categories in 2024—such as Secondary Mangrove Forest and Swamp Bush—may be attributed to improved classification techniques or actual ecological succession within coastal and wetland areas. These new categories indicate ongoing changes in vegetation structure and ecosystem conditions, reflecting both natural processes and the influence of human activities on landscape evolution. Their presence suggests the dynamic nature of ecological transitions in areas subject to tidal, hydrological, and land-use pressures.

Mining land experienced a 65.22% increase, underscoring the intensification of extractive activities during the study period. As mining areas contain no vegetation and therefore no carbon stock, their expansion has direct implications for the city's declining carbon storage capacity. Additionally, modest decreases in ricefields, water bodies, and swamp areas indicate gradual but persistent pressures on agricultural and hydrological systems. Collectively, these patterns demonstrate a development trajectory that prioritizes economic growth while presenting significant challenges for long-term ecological resilience, carbon management, and sustainable spatial planning in Samarinda.

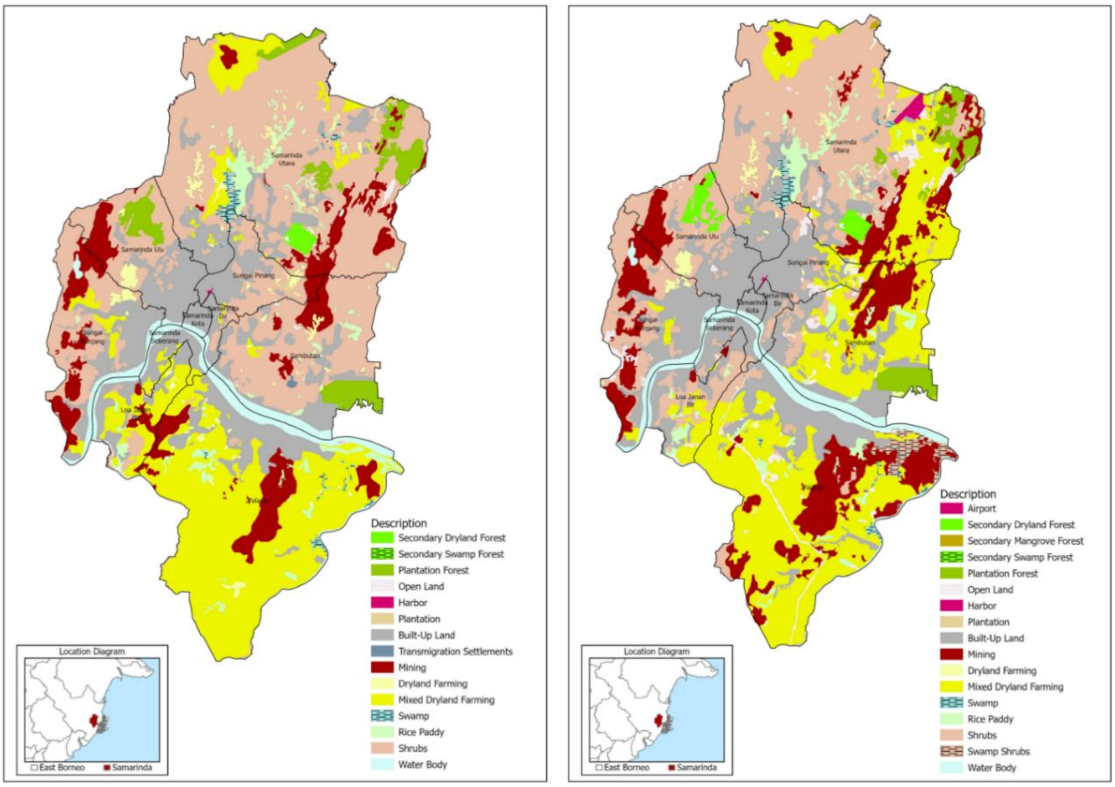

Figure 1. Land Use in 2014 (left) and 2024 (right)

As shown in Figure 1, the spatial pattern of land conversion in Samarinda City over the last decade reveals a massive dominance of extractive activities, with mining areas expanding by 65.22%, from an initial 6,464.33 hectares to 10,680.15 hectares. Geographically, the distribution of mining sites in 2014 appeared more fragmented and primarily concentrated in the northern and southern peripheral areas.

However, by 2024, this pattern transitioned into a more aggregated and aggressively expanded landscape, particularly within the districts of North Samarinda, Sambutan, and Palaran.

This expansion has not only encroached upon forest lands but has also permeated areas formerly classified as mixed dryland farming and shrublands, reflecting intense spatial competition between conservation, production, and extraction functions. Furthermore, the emergence of 'Open Land' areas, which surged by 163.42%, serves as a critical spatial indicator or hotspot for land clearing preceding active mining operations or the development of supporting infrastructure.

B. Carbon Stock Analysis

The precise methodology employed for quantifying the carbon stock in Samarinda City relies on the established calculation approach from the ICLEI Calculator. This method involves a direct multiplication of the carbon stock index specific to each land use type (Ton C/Ha) by the corresponding land area (Ha). Adhering to this rigorous analytical framework, the subsequent sections present the detailed results derived from these calculations, illustrating the total amount of carbon stock present in Samarinda City for both the years 2014 and 2024.

Table 3. Total Carbon Stock in 2014 and 2024

Code	Land Cover Class	Total Carbon Stock (Ton)	
		2014	2024
Hs / 2002	Secondary Dryland Forest	50,867.39	133,994.59
Ht / 2006	Plantation Forest	175,128.77	99,146.09
B / 2007	Shrubs	809,401.61	540,641.81
Br / 20071	Swamp Bush	-	18,057.59
Pk / 2010	Plantation / Garden	6,693.68	10,017.66
Pm / 2012	Built-up Land	64,267.38	76,559.47
T / 2014	Open Land	272.59	3,514.11
Hms / 20041	Secondary Mangrove Forest	0	3,063.06
Hrs / 20051	Secondary Swamp Forest	2,043.46	2.11
Pt / 20091	Dryland Farming	11,278.91	7,751.39
Pt / 20092	Mixed Dryland Farming	505,972.82	546,401.95
Sw / 20093	Ricefield	3,896.40	3,662.24
Bdr/Plb/20121	Harbor	0	0
Bdr/Plb/20121	Airport	0	0
Tr / 20122	Transmigration	389.49	0
Tb / 20141	Mining	0	0
A / 5001	Water Body	0	0
Rw / 50011	Swamp	0	0
Total Carbon Stock		1,630,212.52	1,442,812.07

The table presented provides a detailed estimation of carbon stock, categorizing it by land cover class, corresponding land area (in hectares), and the specific carbon stock constant (measured in tons of carbon per hectare). The data reveals that the total stored carbon stock in the region reached 1,630,212.52 tons. Among the various land cover classes, shrubland (code B/2007) emerged as the most significant contributor to this total carbon stock, accounting for a substantial 809,401.61 tons. Following shrubland, plantation forests contributed 175,128.77 tons, and secondary dryland forests added 50,867.39 tons. This compelling distribution unequivocally indicates that natural and semi-natural vegetation types continue to play an absolutely crucial role in the overall carbon storage capacity of the region.

In stark contrast, several other land classes demonstrated significantly lower or even zero carbon stocks. These include open land, mining areas, ports, and built-up areas, primarily due to the minimal or complete absence of carbon-storing vegetation within these zones. For instance, built-up areas, despite covering over 12,000 hectares, only managed to store approximately 64,267.38 tons of carbon. More critically, mining areas, water bodies, and swamps contributed no carbon stock whatsoever. This discernible pattern clearly underscores that land-use changes gravitating towards extensive infrastructure development and intensified natural resource exploitation can lead to a drastic reduction in an area's vital carbon storage capacity

The table above presents the estimated carbon stock by land cover class in 2024. The total stored carbon stock is recorded at 1,442,812.07 tons. In a shift from 2014, the category contributing the largest carbon stock in 2024 is Mixed Dryland Farming (Pt/20092) with 546,401.95 tons, followed by Shrubs (B/2007) with 540,641.81 tons, and Secondary Dryland Forest (Hs/2002) with 133,994.59 tons. This distribution confirms that while natural vegetation (shrubs and forests) remains critical, certain managed agricultural landscapes like mixed dryland farming now play a primary role in the city's carbon storage. In contrast, Ricefields (Sw/20093) contribute a much smaller fraction of the total stock (3,662.24 tons).

Regarding the expansion of infrastructure, Built-up Land recorded a carbon stock of 76,559.47 tons. Although this area experienced a massive growth of 1,189.16% a figure that methodologically stems from a very low baseline in 2014 its carbon contribution remains limited compared to vegetative lands. This high percentage of growth reflects rapid urban sprawl that prioritizes physical development over high-biomass ecosystems.

In contrast, categories such as ports, airports, mining, water bodies, and swamps have zero carbon stocks, as they lack vegetative biomass capable of storing carbon. Very small carbon stock values were recorded for dryland agriculture (0.01 ha) and secondary swamp forests, reflecting either very limited land area or data input errors. Overall, this table demonstrates that the presence and extent of productive vegetation significantly influence the carbon stock of an area, making it important to consider them in land-use planning and climate change mitigation strategies.

3.2 Discussions

The increase in mining land area from 6,464.33 hectares in 2014 to 10,680.15 hectares in 2024 distinctly indicates a significant and rapid expansion of extractive activities over the past decade (Maus et al., 2022; Zhao et al., 2023).This substantial growth, exceeding 65%, is particularly concerning given that the stored carbon stock within these expanded mining areas remains consistently at zero. This absence of carbon stock is directly attributable to the inherent lack of vegetation in mining sites, which are therefore incapable of absorbing and storing atmospheric carbon (Kartikasari et al., 2019; Yang et al., 2019).Consequently, this phenomenon stands as one of the primary drivers behind the observed decline in the region's total carbon stock, plummeting from 1,630,212.52 tons in 2014 to 1,442,812.07 tons in 2024. In essence, the expansion of mining operations has directly nullified the carbon storage potential previously held by vegetative lands such as natural forests, plantations, shrubs, or mixed agricultural areas (Runyan & Stehm, 2020; Wahyuni & Suranto, 2021; Zheng et al., 2023)

Effectively addressing this critical environmental issue necessitates the adoption of a comprehensive and integrated strategy. The initial, crucial steps involve the diligent reclamation and revegetation of post-mining land. These efforts are vital for restoring the ecological function of the degraded areas and, subsequently, enhancing their capacity for carbon storage (Y. Yang et al., 2018; Machado et al., 2024). The Indonesian government has already laid the groundwork for this through Government Regulation No. 78 of 2010, which legally mandates every mining company to develop and rigorously implement a detailed reclamation plan.

Furthermore, the stringent implementation of mining boundaries and strategic zoning within the Regional Spatial Plan (RTRW) is absolutely crucial to prevent the further conversion of land areas identified as having high conservation value (Palaniyandi & Mahato, 2024; Wiatkowska et al., 2021; Utami et al., 2024). To ensure accountability and progress, regular and systematic monitoring of land cover and carbon stocks must be strengthened. This monitoring should ideally be based on precise satellite imagery and thorough field inventories, aligning with the recommendations provided by the IPCC (2006) and supporting studies on stock-difference methods in watersheds (Purwanto & Sulha, 2024;Qi et al., 2024).Beyond these foundational measures, the implementation of a carbon tax, as legislated by Law No. 7 of 2021 concerning the Harmonization of Tax Regulations, emerges as a potent fiscal instrument. This tax can effectively control carbon emissions emanating from the mining sector while simultaneously providing crucial incentives for companies that successfully undertake land rehabilitation (Brasika et al., 2024;Goh & Lee, 2021).

From a technological and theoretical standpoint, cutting-edge solutions like mineral carbonation and advanced carbon capture technologies offer highly effective mechanisms for mitigating carbon stock depletion linked to mining activities. Emerging theoretical frameworks increasingly highlight the potential of mining waste as a viable and valuable feedstock for long-term carbon sequestration (Stokreef et al., 2022; Zaberi & Kusin, 2018). This innovative concept supports the transformative idea that mining residues, traditionally viewed as an environmental liability, can be converted into valuable carbon sinks.

Furthermore, mounting evidence robustly supports the strategic integration of nature-based solutions, such as carefully planned earthworks and extensive revegetation programs, with engineered mineral carbonation processes (Ruiz et al., 2023;Weiler et al., 2024; Liu et al., 2022). This hybrid approach is designed to significantly enhance post-mining carbon stock recovery. The continuous development of novel reactor designs and accelerated carbonation processes, including sophisticated solvent treatments and biotechnological enhancements via microbial activity, significantly expands the theoretical landscape (Pandey & Bhaduri, 2023; Zhang et al., 2020). Theoretical insights also extend to the strategic combination of carbon capture with resource recovery, such as the simultaneous extraction of rare earth elements during the carbonation process, effectively linking carbon mitigation with broader circular economy principles (Sim et al., 2022)

Lastly, the practical feasibility of implementing advanced green mining technologies is gaining considerable traction. This includes transport electrification within mining operations and the integration of renewable energy sources to reduce direct emissions (Onifade et al., 2024; Aydogdu et al., 2024) Integration of carbon mineralization with innovative recharge mining methods, particularly the continuous extraction and continuous recharge (CECB) approach which utilizes CO_2 mineral recharge bodies, presents a novel solution to reduce overburden migration and achieve substantial carbon sequestration under ambient conditions (Xu & Ma, 2024; Xu et al., 2022)

Conclusion

This study successfully fulfills its primary objective of quantifying the decadal impact of land-use conversion on terrestrial carbon stocks in Samarinda City. The findings reveal a significant depletion of the city's total carbon stock, which fell from 1,630,212.52 tons in 2014 to 1,442,812.07 tons in 2024. This decline is fundamentally driven by a 65.22% expansion of coal mining areas, which grew from 6,464.33 hectares to 10,680.15 hectares during the study period. Because these extractive zones lack vegetative biomass, they contribute zero carbon storage, effectively nullifying the sequestration potential of previously existing forests and shrublands.

This research advances the field by providing a high-resolution, city-scale analysis that bridges the critical gap between broad provincial assessments and local municipal planning needs. Scientifically, the work explicitly demonstrates the "carbon penalty" associated with industrial and urban expansion in a complex urban-mining interface. These results provide a clear scientific justification for revising regional governance, specifically through the integration of strategic zoning within the Regional Spatial Plan (RTRW) and the strict enforcement of post-mining reclamation mandates as regulated under Government Regulation No. 78 of 2010. Furthermore, the findings support the implementation of fiscal instruments, such as the carbon tax legislated by Law No. 7 of 2021, to regulate emissions and incentivize corporations toward measurable land rehabilitation.

To mitigate further carbon stock loss, this study indicates that possible applications should include adopting advanced technological solutions such as mineral carbonation of tailings and the Continuous Extraction and Continuous Recharge (CECB) method to transform mining waste into active carbon sinks. Future extensions of this work are essential and should incorporate field-based biomass measurements and detailed below-ground soil organic carbon (SOC) assessments to enhance the precision of regional storage estimates. Ultimately, a balanced approach that integrates green infrastructure with sustainable mining practices is recommended to ensure long-term ecological resilience and climate-resilient development for future generations.

Implication

The quantitative findings of this study reveal a decline in total carbon stock from 1,630,212.52 tons in 2014 to 1,442,812.07 tons in 2024, driven largely by a 65.22% expansion in mining areas. These results translate into three critical implications for policy and practice. The significant expansion of mining concessions necessitates the stringent implementation of mining boundaries and strategic zoning within the Regional Spatial Plan (RTRW). Given that mining areas characterized by total vegetation removal possess zero carbon stock, spatial planning must prioritize the protection of remaining high carbon zones such as secondary dryland forests and shrublands from conversion into extractive use. Furthermore, in light of the 1,189.16% increase in built-up land, integrating green infrastructure into urban development is critical to offset the carbon losses incurred by land conversion.

From a governance perspective, enforcing post-mining restoration is paramount, as mining expansion directly nullifies the carbon sequestration potential of vegetative landscapes. The government must rigorously enforce Government Regulation No. 78 of 2010, which mandates comprehensive reclamation and revegetation plans for all mining operators. Beyond conventional revegetation, the adoption of advanced technologies such as the mineral carbonation of mine tailings and 'Continuous Extraction and Continuous Recharge' (CECB) methods—should be integrated into regulatory targets to transform mining waste into active carbon sinks.

To ensure accountability, municipal authorities must strengthen the systematic monitoring of land cover and carbon stocks using high-precision satellite imagery and field inventories aligned with IPCC guidelines. Such data are essential for accurate climate mitigation reporting and the implementation of fiscal instruments, such as the carbon tax legislated by Law No. 7 of 2021. This tax mechanism serves a dual-purpose regulating emissions from the extractive sector while incentivizing corporations to achieve measurable increases in post-mining carbon sequestration.

Limitations

This study has some limitations that should be noted to properly understand its context and findings. The analysis relies heavily on remote sensing data and GIS tools to map land use changes, which may be subject to inherent inaccuracies in classification and boundary detection. The carbon stock quantification uses the ICLEI calculator, which provides estimations based on land type and area but may not account for more granular, site-specific variables like soil carbon content, biomass density, and specific land management practices that can influence carbon storage. The data also shows new land cover classes in 2024, which could be due to refined mapping techniques rather than actual new ecological developments. Additionally, some categories, such as dryland agriculture and secondary swamp forests, show very small carbon stock values, which may reflect very limited land area or potential data input errors. These factors may affect the precision of the carbon stock calculations and the overall generalizability of the results, highlighting the need for further research with more detailed field inventories and local data.

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