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Modeling of Carbon Emissions and Sequestration Due to Land Cover Changes in Makassar Using Geospatial Technology

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Abstract
Land-use change significantly affects carbon emissions, particularly in rapidly growing cities such as Makassar. This study uses geospatial technology to analyze the impact of land cover changes on carbon emissions and sequestration in Makassar City from 2022 to 2041. The Rapid Carbon Stock Appraisal (RaCSA) method and the QUES-C feature of the LUMENS software were utilized to model land cover changes based on the Makassar City spatial planning scenario (RTRW). The results indicate that expanding residential areas and reducing green spaces, such as mangrove forests and agricultural land, have increased carbon emissions. However, carbon sequestration in certain areas, especially in the Tallo District and reclamation areas, has increased significantly due to the establishment of local protection zones. This study highlights the importance of spatial planning that supports the protection and restoration of green spaces to enhance carbon sequestration capacity and support sustainable development strategies in Makassar City.

Keywords: Land Cover Change, Carbon Emissions, Carbon Sequestration, Makassar City Spatial Plan (RTRW), Geospatial Technology

INTRODUCTION

Land-use change significantly drives global carbon emissions, especially in rapidly growing urban areas. Makassar City, one of the largest cities in Indonesia, has experienced considerable land-use changes due to population growth and urbanization. The conversion of natural vegetation into residential, commercial, and industrial areas has increased greenhouse gas emissions, particularly carbon dioxide (CO2) (Zhu et al., 2023). With rising awareness of the impacts of climate change, there is an urgent need to develop effective land management strategies to reduce carbon emissions and enhance carbon sequestration in urban areas.

Numerous studies emphasize the importance of proper conservation and management strategies to enhance vegetation carbon sequestration (Yu et al., 2015). For instance, sustainable land-use practices and forest protection can help reduce carbon stock losses and facilitate ecosystem recovery. In this context, a better understanding carbon sources' spatial and temporal distribution is crucial for identifying areas needing conservation intervention (Zhu et al., 2022). Therefore, policymakers need to develop evidence-based approaches in spatial management focused on reducing carbon emissions and protecting local ecosystems (Peng, 2024).

The main issue in this study is the increase in carbon emissions due to land cover changes in Makassar City, primarily caused by converting natural land into residential and industrial areas. This process reduces the local ecosystem's ability to store carbon and increases carbon emissions into the atmosphere, contributing to global climate change. The negative impacts of these land cover changes are of international concern, highlighting the urgent need for developing effective spatial management strategies to balance development needs and environmental preservation.

Standard solutions to this problem involve implementing geospatial technologies, such as remote sensing and geographic information systems (GIS), to monitor land cover changes and evaluate their impact on carbon emissions and sequestration. This approach allows real-time identification of land cover changes, which can be used to support better policy decisions and timely land management interventions. Using the Rapid Carbon Stock Appraisal (RaCSA) method and the QUES-C feature in the LUMENS software, this study aims to measure carbon emission levels and identify the carbon sequestration capacity of various land cover types in Makassar.

Geospatial technology, such as remote sensing and GIS, has proven effective in monitoring and analyzing land-use changes and carbon emissions. Research shows that satellite imagery, such as Landsat, can monitor carbon stocks in the forestry sector and evaluate land cover changes over time (Tosiani et al., 2018). For example, a study by Nguyen et al. (2016) in Palembang City used remote sensing technology and LUMENS to analyze land cover changes and measure carbon stock losses due to CO2 emissions. This research highlights the importance of monitoring land cover changes to assess their impact on carbon stocks (Eddy, 2023; Liu et al., 2014).

Sustainable urban planning requires implementing effective carbon mitigation strategies, such as developing green open spaces and applying the green city concept (Ahmad, 2023). These concepts help reduce carbon emissions and improve the quality of life by providing healthier and more comfortable environments. Studies show that cities adopting green and creative city approaches can more effectively address urban challenges and support sustainable development (Sari et al., 2020). Efforts to enhance carbon sequestration support several United Nations Sustainable Development Goals (SDGs), particularly SDG 13, "Climate Action," and SDG 15, "Life on Land." Effective land-use strategies can help achieve SDG targets by reducing carbon emissions and preserving terrestrial ecosystems (Rodrigues et al., 2023; Yin et al., 2023). By leveraging technology and data, cities can optimize resource use, reduce carbon emissions, and enhance community well-being.

While many studies have explored the relationship between land-use changes and carbon emissions, several research gaps must be addressed to understand the specific impact of land cover changes in Makassar City. For example, although some studies have evaluated the spatial and temporal distribution of carbon sources (Zhu et al., 2022), there is still a need to explore the long-term impact of land cover changes on carbon sequestration capacity across different ecosystem types. A study by Sawirdin (2023) highlights the crucial role of remote sensing technology in estimating carbon stocks in forest ecosystems and the impact of land-use changes on carbon stocks across extensive areas.

Furthermore, exploring land-use strategies that effectively minimize carbon emissions and enhance carbon sequestration is essential. Previous studies have highlighted the importance of implementing sustainable land management and conservation strategies to increase vegetation carbon sequestration capacity (Zhu et al., 2023). Research by Shinde et al. (2022) indicates that understanding the relationship between land-use systems and carbon stocks is crucial, as different land-use systems can have varying impacts on carbon balance. Therefore, accurate regional carbon stock assessments and analyses of their relationship with land-use patterns are essential for ecosystem protection and sustainable development (Qi, 2023).

The land cover changes in Makassar City involving the conversion of natural land into residential and industrial areas are expected to trigger a significant increase in carbon emissions. By leveraging remote sensing and GIS technology, this study focuses on measuring carbon emission levels and evaluating the carbon sequestration capacity of various land cover types in the city. This study analyzes the impact of land cover changes on carbon balance using the Rapid Carbon Stock Appraisal (RaCSA) method and the QUES-C feature in the LUMENS software. This approach provides insights into carbon emissions and identifies land-use strategies that can support sustainable urban planning in Makassar. Thus, this study contributes to developing spatial management strategies that balance development needs and environmental preservation, supporting climate change mitigation efforts at the local level.

RESEARCH METHODS

Research Location

This study was conducted in Makassar City, the capital of South Sulawesi Province, Indonesia. Makassar is situated in the southwestern part of Sulawesi Island and covers an area of approximately 1,993 km^2, as shown in Figure 1.

This region was selected as the research location due to its significant land-use change dynamics and its role as an economic and governmental hub. As a rapidly developing metropolitan city, Makassar faces substantial challenges in environmental management, mainly related to carbon emissions and sequestration due to land cover changes.

Research Data

The study utilized two different sets of land cover data. The first dataset comprises land cover information for 2022, obtained from the interpretation of Pleiades satellite imagery with a multispectral resolution of 2 meters and a panchromatic resolution of 0.5 meters. This data was sourced from the Green Open Space Identification Activity Document and the Land Quality Index of Makassar City. The second dataset represents transformed land cover from the Makassar City Spatial Pattern Plan, derived from the Revised RTRW of Makassar City for 2022-2041. These datasets provide the necessary information to understand land cover changes and their impact on carbon stocks in the study area.

Research Stages

This study employed the Rapid Carbon Stock Appraisal (RaCSA) method (Markum et al., 2013; Siarudin et al., 2021), using the QUES-C feature in the LUMENS software to analyze land cover changes and their impact on carbon emissions and sequestration. The LUMENS software was utilized to model land cover changes based on the RTRW scenario. This model allows for an in-depth analysis of how spatial planning changes can affect carbon stocks and sequestration in Makassar City.

The first stage of the research involved identifying existing land cover classifications from the available data. Each land cover type was mapped to determine its carbon stock level based on land cover classification. Carbon stock values for each land cover type were derived from previous studies that estimated carbon stock values in tons per hectare for each land use type

(Harja et al., 2011; Rochmayanto et al., 2014). Subsequently, carbon emissions were calculated by comparing land cover changes between the 2022 data and the RTRW 2022-2041 scenario. Carbon emissions were calculated by multiplying the change in carbon stock (ΔC) resulting from land cover change by the area of change (A) using the formula:

$$CE = \Delta C \; x \; A \qquad (1)$$

where E is total carbon emissions (tons C), ΔC is change in carbon stock per hectare (tons C/ha), A is area of change (ha).

Carbon sequestration, the process of absorbing carbon dioxide from the atmosphere, was calculated by identifying land cover types that contribute to carbon absorption, such as forests and plantations. The carbon sequestration rate (R) was obtained from relevant literature and expressed in tons of carbon per hectare per year (tons C/ha/year). Total carbon sequestration was calculated using the formula:

$$S = R \; x \; A \; x \; T \qquad (2)$$

where S is total carbon sequestration (tons C), R is rate of carbon sequestration (tons /ha/year), A is area of land cover (ha), and T is period (years).

This approach is expected to provide helpful information for spatial planning and environmental management in Makassar City, supporting local climate change mitigation policies. The results of this study provide a basis for sustainable land management strategies by considering aspects of carbon emissions and sequestration.

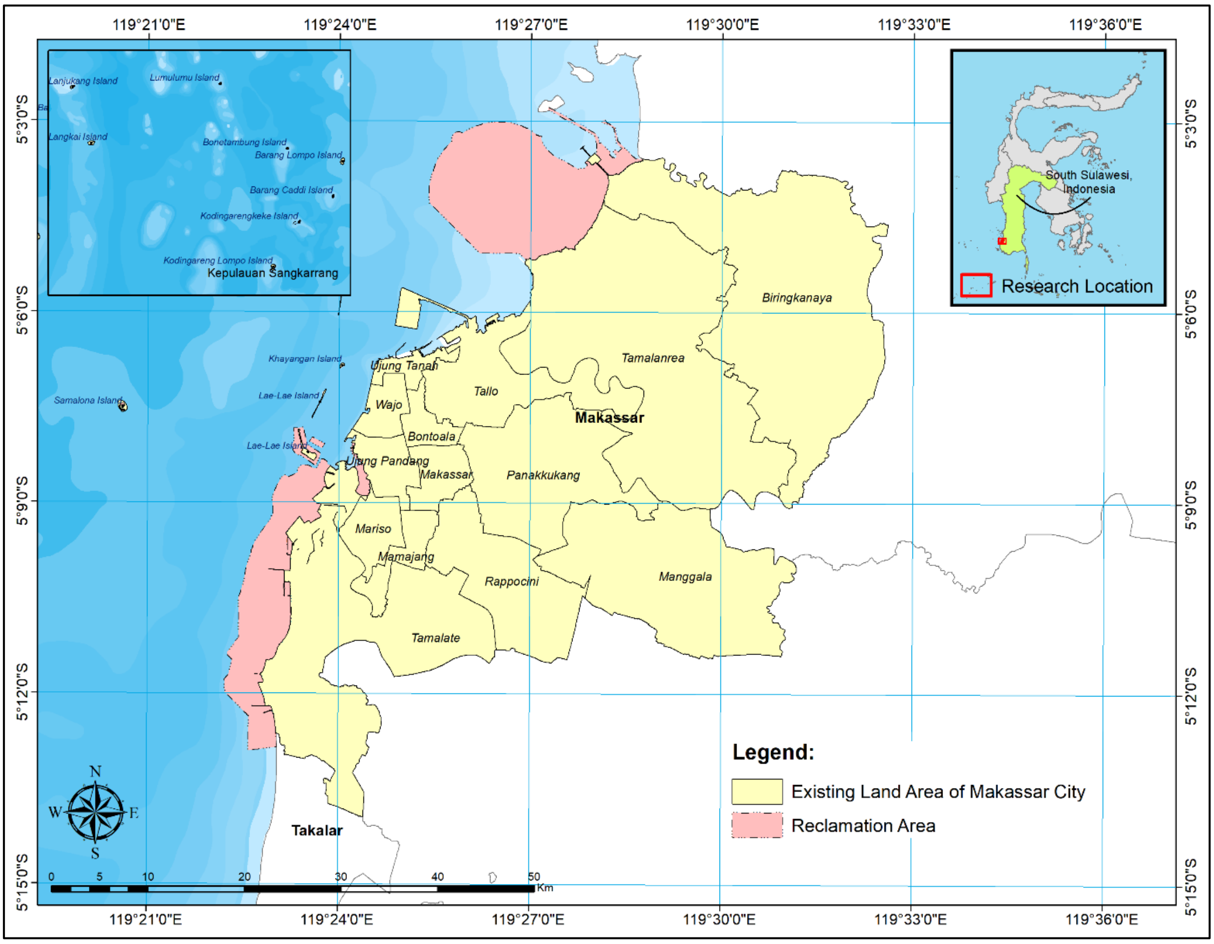

Figure 1. Research Map Location

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RESULTS

Land Cover Change

The land cover change in Makassar City from 2022 to the RTRW 2041 scenario reflects a complex dynamic in the city's land use. Overall, there is a significant trend of land conversion from agriculture and aquaculture to residential areas, public facilities, and industrial zones. However, the RTRW 2041 scenario offers improvements compared to the current land cover conditions, particularly with increased local protection areas and planned green spaces, especially in reclamation lands.

The data show that the area designated for residential use increased from 834,206 hectares in 2022 to 980,600 hectares in 2041. Meanwhile, agricultural land experienced a drastic decrease from 415,924 hectares to just 48,728 hectares. Although there is a decline in specific green spaces, such as agricultural lands and mangrove forests, which decreased from 7,063 hectares to 6,436 hectares, the RTRW 2041 scenario introduces more local protection areas to expand the city's green spaces, particularly in reclamation areas. The regional protection area increased significantly from 13,569 to 99,024 hectares, reflecting the government's efforts to create a more sustainable environment amid increasing urbanization pressures.

The land cover map visualizations from 2022 to 2041 (Figure 2) depicts significant changes across various districts in Makassar City. Residential areas experienced massive expansion, replacing agricultural lands, shrubs, and aquaculture areas. In Biringkanaya District, the dominant land conversion from agriculture to residential areas is evident, with some aquaculture areas also transforming into residential and public facility zones, reflecting rapid settlement growth and significantly reducing green spaces. However, the increase in local protection areas in the RTRW 2041 scenario provides hope that green spaces can still be maintained and expanded.

In the Tamalanrea District, the visualization shows that agriculture and aquaculture have primarily been converted into residential and public facilities, reflecting intense urbanization pressures. Some areas that were previously green have been transformed into industrial zones. Nevertheless, the RTRW 2041 scenario introduces measures to preserve and expand green areas through the increased number of green open spaces in this area. The research by Fitriani et al. (2022) supports these findings, showing that urban morphological expansion in Makassar involves significant land-use changes, often leading to the reduction of green areas.

Tamalanrea District demonstrates a massive transition from agricultural lands and shrubs to residential and mixed areas, illustrating intense urban sprawl in this area. Rapid residential growth has decreased natural lands that previously supported carbon sequestration. However, the RTRW 2041 scenario indicates an increase in green spaces and protection areas that can offset these urbanization pressures. The increase in green open spaces in reclamation areas, for instance, shows that despite urbanization, there is still a commitment to maintaining the balance of the city's ecosystem. Fajriani et al. (2022) also noted that land cover changes in built-up areas show a significant upward trend that needs to be balanced with better planning to reduce environmental impacts.

Reclamation areas are among the regions showing the most significant changes in the RTRW 2041 scenario. The conversion of water bodies to various land-use types, such as residential, public facilities, and industrial areas, alongside a significant increase in local protection areas from 25,528 hectares to more than 134,400 hectares. This reflects a more sustainable approach to city spatial planning, where green spaces and protection areas become a primary focus. Surya et al. (2021) identified that environmental sustainability in urban planning is critical, especially in rapid city growth like Makassar. Manggala District shows a significant reduction in agricultural area due to conversion to residential areas. Still, with the RTRW 2041 scenario, an increase in urban forest area is expected to help maintain ecosystem balance. Meanwhile, in Tallo District, although mangrove land has decreased, the RTRW 2041 scenario introduces measures to protect and restore this area, especially along coastal regions.

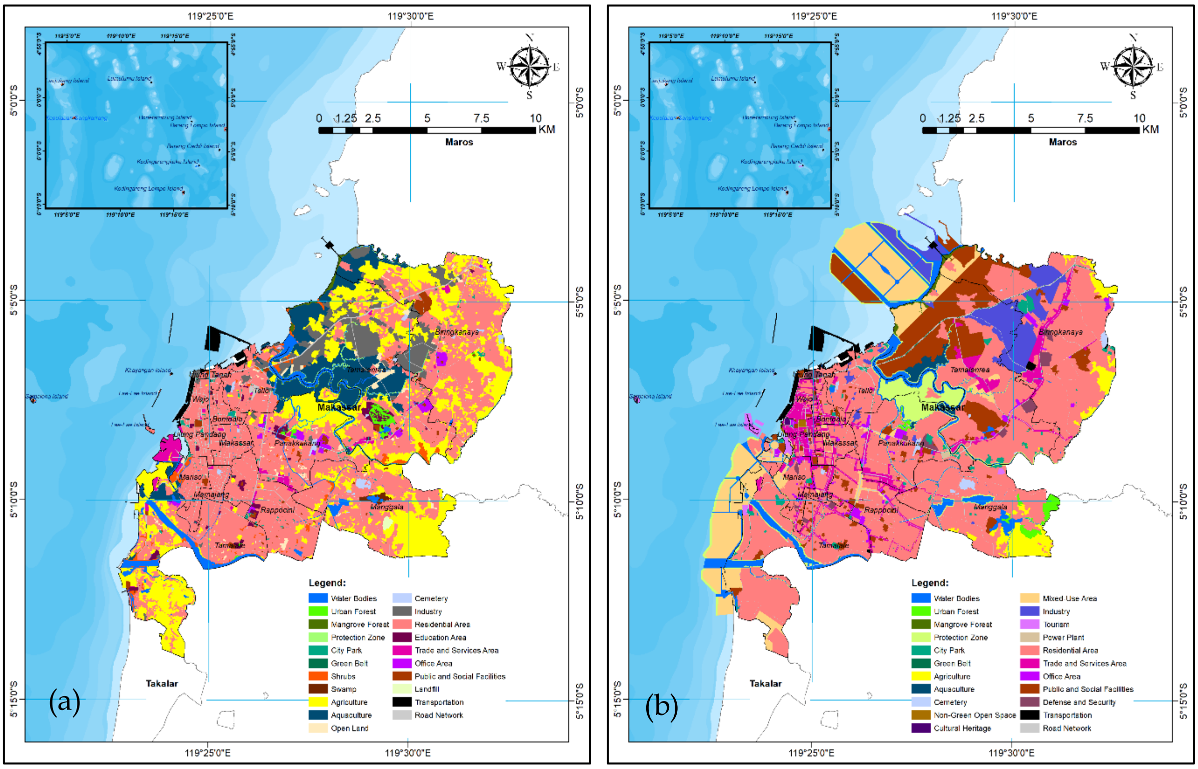

Figure 2. Land Cover Map for 2022 (a) and Land Cover Scenario Based on RTRW 2041 (b)

Carbon Stock, Emissions, and Sequestration

The average carbon stock in Makassar City shows significant variation between districts in 2022, with some areas like Panakkukang and Tallo having higher carbon stocks than other regions (Figure 3). By 2041, carbon stock will significantly increase in several districts, particularly in reclamation areas and Tallo. For instance, Panakkukang District recorded an increase from 1,441 tons of C/ha in 2022 to 4,574 tons of C/ha in 2041, while Tallo increased from 1,028 tons of C/ha to 735 tons of C/ha. Sangkarrang Islands also experienced a significant increase from 613 tons of C/ha in 2022 to 3,145 tons of C/ha in 2041, indicating substantial land-use changes that enhance carbon stocks in these areas.

However, some districts experienced a decrease in carbon density, such as Bontoala, which declined from 1,799 tons of C/ha in 2022 to 898 tons of C/ha in 2041, and Makassar, which saw a reduction from 716 tons of C/ha to 418 tons of C/ha over the same period. This decrease indicates that land conversion negatively impacts carbon stocks in these areas (Figure 4)

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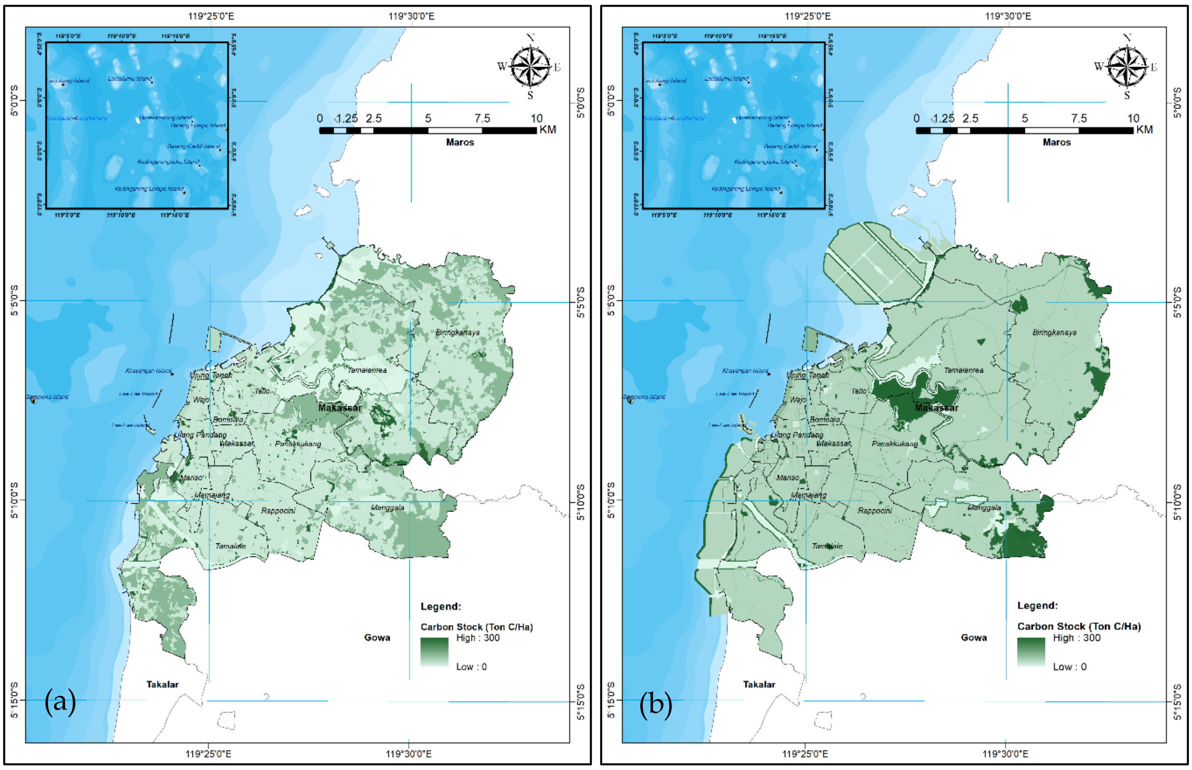

Figure 2. Carbon Stock Map for 2022 (a) and 2041 (b)

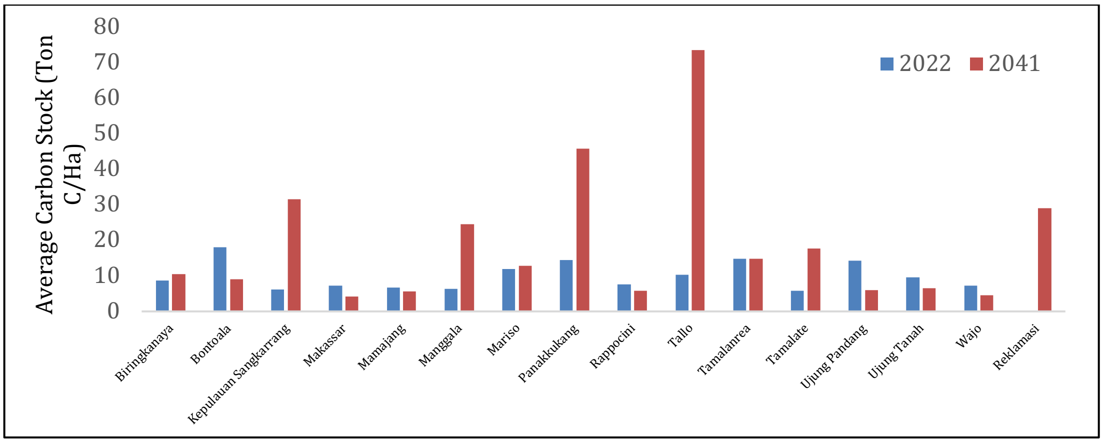

Figure 3. Average Carbon Stock

The increase in carbon stock in some areas aligns with Kurniawati (2021) findings that carbon stock values can increase alongside land-use changes, as seen in Surabaya City from 2000 to 2020, which experienced a 435% increase. Conversely, research by Sumarlin et al. (2021) in Ketapang Regency highlights that environmental degradation due to poorly managed land conversion can lead to decreased carbon stocks, as observed in Bontoala and Makassar.

Fadhli et al. (2021) study in Aceh revealed that carbon stock is greatly influenced by the number and size of trees, where the felling of large-diameter trees can reduce the amount of stored carbon. This condition is relevant to the decline in carbon stocks in several districts in Makassar. On the other hand, research by Randa (2024) and Susanto et al. (2021) shows that vegetation diversity and land age play vital roles in maintaining carbon stocks, as reflected in the increased carbon stock in Makassar's reclamation areas.

From 2022 to 2041, the total carbon emissions in Makassar City are estimated to reach 264,230.57 tons of CO2-eq, while carbon sequestration amounts to 1,218,576.58 tons of CO2-eq. This results in a harmful net emission of -954,346.01 tons of CO2-eq, indicating that the carbon sequestration capacity in this region far exceeds carbon emissions, as shown in Table 1 and Figure 4. Several districts exhibit very low emission rates. For instance, Tamalanrea District has an emission rate of -0.01 tons of CO2-eq/ha/year, indicating an increase in net carbon stock. Tallo District recorded the most significant emission rate of -1.221 tons of CO2-eq/ha/year, marking an extraordinarily large increase in carbon stock, primarily due to the increase in local protection areas.

Table 1. Carbon Emission and Sequestration Levels in Makassar City for 2022-2041

No	District	Total Emissions (Ton CO2-eq)	Total Sequestration (Ton CO2-eq)	Net Emissions (Ton CO2-eq)	Emission Rate (Ton CO2/Ha,yr)
1	Biringkanaya	43.206,29	68.052,44	-24.846,15	-0,35
2	Bontoala	6.196,79	452,42	5.744,37	1,74
3	Kepulauan Sangkarrang	649,73	8.678,83	-8.029,10	-4,89
4	Makassar	2.933,24	33,04	2.900,20	0,58
5	Mamajang	2.418,87	1.439,24	979,63	0,2
6	Manggala	11.560,12	153.790,02	-142.229,90	-3,49
7	Mariso	6.855,76	7.826,85	-971,09	-0,18
8	Panakkukang	26.872,41	197.986,81	-171.114,40	-6,05
9	Rappocini	12.722,95	5.177,52	7.545,43	0,35
10	Tallo	9.187,02	256.508,94	-247.321,92	-12,21
11	Tamalanrea	108.734,18	109.682,99	-948,80	-0,01
12	Tamalate	18.662,62	133.110,93	-114.448,30	-2,28
13	Ujung Pandang	9.310,74	459,01	8.851,72	1,62
14	Ujung Tanah	2.692,19	1.159,98	1.532,21	0,59
15	Wajo	2.217,92	139,77	2.078,15	0,54
16	Reclamation Area	9,74	274.077,79	-274.068,05	-5,6

The primary contributors to carbon emissions in many districts include land conversion from City Parks to Residential Areas and City Parks to Public and Social Facilities. The conversion of Mangrove Forests to Water Bodies in Tallo also represents a significant source of emissions, causing substantial carbon releases. The study by (Jamaludin et al., 2020) emphasizes that land-use changes from vegetation to agriculture, as seen in many other regions, can also contribute to carbon emissions in urban areas.

On the other hand, the most significant carbon sequestration in Makassar City occurs due to the conversion of Water Bodies to Local Protection in reclamation and Tallo areas, significantly increasing carbon stocks in these areas. Additionally, converting Agricultural Land and Aquaculture to Local Protection in Tamalanrea and Tamalate contributes significantly to increased carbon sequestration. Research by Rahman (2023) underscores the importance of preventing forest degradation and land-use change, particularly in tropical regions like Indonesia, as an effective way to reduce carbon emissions. Research by Meidiana (2024) highlights the importance of the absorption capacity of urban green open spaces against emissions from the transportation sector as an effort to reduce

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carbon emissions in urban environments. This is highly relevant to efforts in Makassar City to increase green open spaces and local protection areas, which are crucial in offsetting carbon emissions from various regional sources.

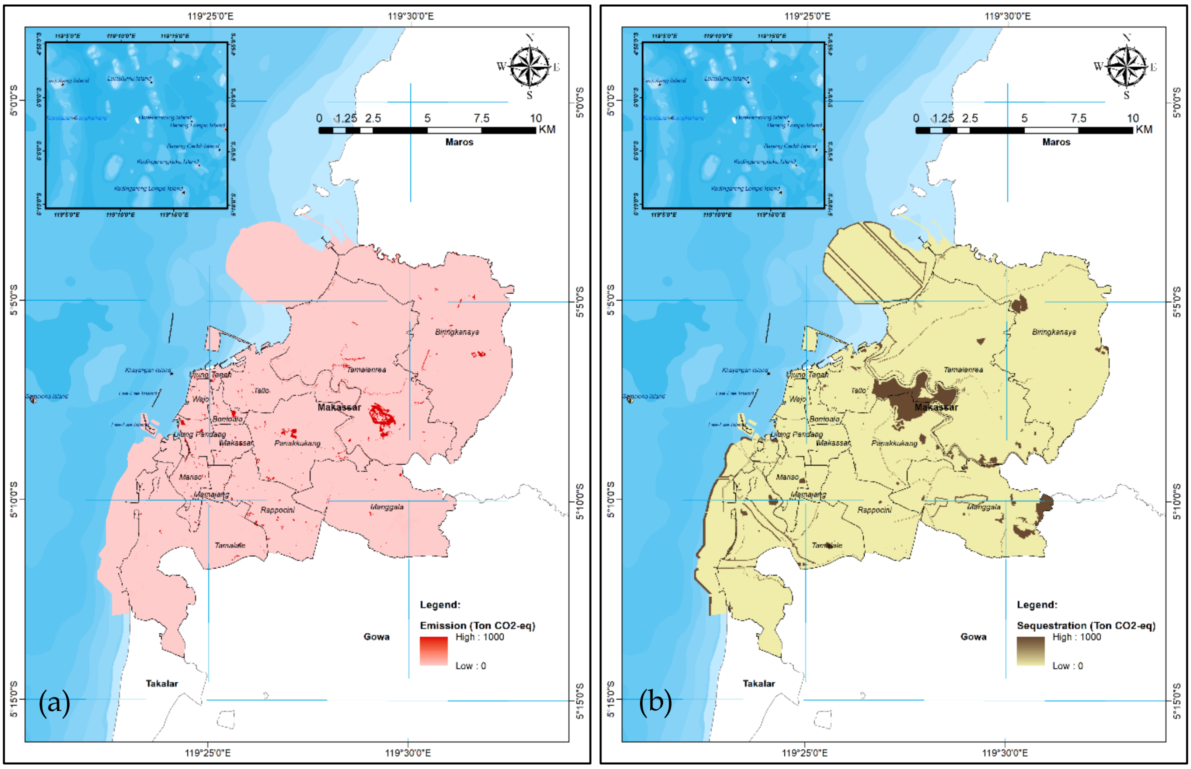

Figure 4. Emission Levels Map (a) and Sequestration (b) for the Period 2022-2041

The changes in land cover in Makassar City between 2022 and 2041 provide crucial insights into the impact of land-use changes on carbon stocks and emissions. The expansion of residential areas and the reduction of green spaces, such as agricultural land, urban forests, and mangrove forests, have decreased carbon storage capacity in several districts. Lands that previously acted as carbon sinks have now become sources of carbon emissions due to increased human activity related to urbanization and economic growth.

In coastal areas, such as Tallo District, the decline of mangrove forests and aquaculture has reduced the ability to absorb carbon. However, it is essential to note that Tallo District has significantly increased carbon sequestration, thanks to protection and revegetation efforts to enhance carbon uptake. This indicates that with proper planning and policy, the negative impacts of land conversion can be offset by increasing carbon sequestration capacity. These findings are consistent with the research of Selvia et al. (2023), which shows that land cover changes can significantly affect carbon stocks, either as sources or sinks, depending on the type of use, which shows that land cover changes can significantly affect carbon stocks, either as sources or sinks, depending on the type of use (Febrianti, 2023).

However, revisions to the RTRW are expected to improve carbon management by expanding green areas and enhancing carbon sequestration, as seen in Tallo District. These efforts align with the Sustainable Development Goals (SDGs), emphasizing the importance of sustainable development and reducing carbon emissions (Dadzie et al., 2020; Sulhadi, 2022). These efforts are part of the integration of SDG policies, emphasizing a balance between economic, social, and environmental sustainability.

The reclamation projects in the northern part of Makassar City illustrate how coastal development policies and the expansion of urban areas into new lands have driven land cover changes that can potentially disrupt coastal ecosystems and carbon stocks. However, if managed well, these land-use changes can also enhance carbon sequestration, as seen in the reclamation areas and Tallo District, where increased carbon sequestration reflects the significant potential of proper spatial planning.

The conversion of agricultural and plantation lands into residential areas, as observed in Tamalate and Rappocini Districts, has resulted in the release of carbon stored in vegetation and soil. Research by (Jamaludin et al., 2020) indicates that such land-use changes can contribute to increased carbon emissions into the atmosphere. This underscores the need for policies that support sustainable land management to mitigate the negative impacts of such conversions.

In terms of carbon density, significant changes have been observed in several areas, such as Tallo and the Sangkarrang Islands, where increases in carbon stocks have occurred. This increase is often associated with converting non-productive land into protective areas or other green spaces, highlighting the importance of sustainable land management to maintain carbon stock balance. Research by Kurniawati (Kurniawati, 2021) supports the importance of land-use planning approaches oriented toward low-carbon development as a critical strategy for achieving sustainability.

The rise in carbon emissions carries potential risks, including ecological losses and socio-economic impacts. Increased carbon emissions, mainly from converting green spaces like mangrove forests and agriculture into residential areas, can degrade environmental quality, raise local temperatures (urban heat island effect), and disrupt hydrological cycles. The socio-economic impacts are also significant, particularly in the increased frequency of natural disasters affecting the residents of Makassar City, especially in coastal areas and economic sectors vulnerable to climate change.

Districts such as Bontoala, Makassar, and Rappocini have shown significant carbon emissions increases due to converting green spaces into residential, public, or social facilities. Research by Luhulima et al. (2020) supports these findings, indicating that land-use changes can impact CO2 carbon absorption capacity reduction. This impact is exacerbated by the reduction of green spaces essential for the balance of urban ecosystems, ultimately affecting residents' quality of life.

Carbon sequestration plays a crucial role in mitigating carbon emissions in Makassar City. The increase in carbon sequestration in areas like Tallo and reclamation zones indicates that appropriate policies can help offset high carbon emissions. The conversion of non-productive or degraded land into urban forests or protected areas can significantly increase carbon stocks and reduce net emissions. Research by Meidiana (Meidiana, 2024) emphasizes the importance of urban green spaces in reducing emissions from the transportation sector, which is relevant in the context of Makassar City.

Spatial planning policies that support green space preservation, reforestation, and sustainable land use are essential to supporting carbon sequestration. Additionally, policies promoting green infrastructure development and mitigating the environmental impacts of development should be more broadly implemented in Makassar City. Integrating SDG policies into urban spatial planning, as suggested by Dodds & Wong (2023), will be a strategic step to ensure that urban development is not only oriented towards economic growth but also maintains environmental sustainability.

CONCLUSIONS

This study demonstrates that land cover changes in Makassar City from 2022 to 2041 have significantly impacted carbon emissions and sequestration. Expanding residential areas and reducing green spaces, including mangrove forests and agricultural land, have increased carbon emissions and reduced sequestration capacity in certain areas. However, with appropriate spatial planning, as implemented in Tallo District and reclamation areas, carbon sequestration can be significantly enhanced, helping to offset generated emissions. This research highlights the importance of spatial policies supporting green space protection and restoration to strengthen carbon absorption capacity and ensure environmental sustainability in Makassar City.

Regarding policy implications, this study suggests that policymakers should prioritize protecting and restoring areas with high carbon storage potential, such as forests and wetlands. Policies that promote reforestation, agricultural land maintenance, and coastal area protection are essential for reducing carbon emissions and enhancing resilience to climate change. The study also has important implications for sustainable development strategies in Makassar City, supporting efforts to achieve the Sustainable Development Goals (SDGs), particularly about climate change mitigation and land-use management. By integrating these findings into spatial policies, Makassar City can more effectively balance economic, social, and environmental development to achieve long-term sustainability.

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