Jurnal Presipitasi
Media Komunikasi dan Pengembangan Teknik Lingkungan
e-ISSN: 2550-0023

Vol 22, No 3, 2025, 937-949
Article available at [homepage presipitasi]()

Regional Case Study

Assessing Urban Carbon Sequestration Capacity under Land Use Changes

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Abstract

A significant amount of global greenhouse gas (GHG) emissions comes from Indonesia, largely driven by deforestation and land degradation. As a developing nation, it is also dealing with the growing pressures of urban expansion. This study assesses the distribution of carbon stock in Parepare City, South Sulawesi, Indonesia. Notably, Parepare City has not yet experienced extensive land-use transformations, retaining substantial carbon stock, which positions it as a proactive case study for preventing future carbon loss amidst ongoing urbanization. Using the InVEST Carbon Storage and Sequestration model with SPOT 7 satellite imagery (2016) and global carbon density data, the research quantifies carbon storage across various land use/land cover (LULC) types. Analysis reveals natural ecosystems, particularly mixed forests and fields, hold the highest carbon storage potential. The total estimated carbon stock in Parepare City is 1,456,909.41 Mg C. These findings emphasize the urgent need for climate-responsive land management, including forest conservation, and urban greening, to enhance local carbon sinks and support Indonesia's climate change mitigation goals. This assessment provides crucial insights for urban planners and policymakers to balance growth with ecosystem conservation for a sustaooinable future.

Keyword: Climate change mitigation; Indonesia; InVEST; land use change; model; urban carbon stocks

1. Introduction

Global climate change is unequivocally recognized as a paramount environmental challenge of our time. A significant driver of rising atmospheric carbon levels stems from land use and land-use change

(LULUCF), encompassing activities like deforestation, forest degradation, agricultural expansion and urban growth. These actions release large amounts of stored carbon and reduce the future capacity of ecosystems to sequester carbon, thereby reinforcing a feedback loop that accelerates climate change (Friedlingstein et al., 2023; Houghton & Nassikas, 2017). Recent global assessments show that tropical countries, especially Brazil, Indonesia, and the Democratic Republic of Congo, contribute a disproportionate share of global net LULUCF emissions, largely due to extensive forest loss and land conversion (Friedlingstein et al., 2023; Hansis et al., 2015).

Indonesia stands out as a carbon hotspot because of its vast tropical forests, peatlands, and mangrove ecosystems, among the most carbon-rich in the world. These ecosystems are increasingly threatened by agricultural expansion, logging, palm oil plantations, and infrastructure development, making Indonesia one of the top global emitters from land-use change (Murdiyarso et al., 2015; Warren et al., 2017) including land extension in the mining sector. Particularly concerning is the degradation of peatlands through drainage and fire, which contributes significantly to national greenhouse gas (GHG) emissions (Leifeld & Menichetti, 2018). However, Indonesia has demonstrated considerable commitment to advancing carbon capture, utilization, and storage (CCUS) technologies as part of its national strategy to meet climate goals, including plans to launch 15 CCUS projects by 2026 (Ramadhan et al., 2024). Moreover, mangrove ecosystems in regions such as South Sulawesi provide substantial carbon storage services; however, ongoing degradation due to aquaculture expansion and urban development poses a significant threat to this capacity (Indriyani et al., 2020).

Parepare City, located in South Sulawesi, was selected for this study due to its relatively small built-up area compared to surrounding natural landscapes, making it an ideal case for assessing carbon dynamics in the context of urban expansion. Urban sprawl is known to reduce vegetative carbon sequestration by converting green areas, such as forests, wetlands, and agricultural lands—into built environments. A study on urban land conversion in China found that vegetation carbon uptake in newly urbanized areas declined significantly after development, underscoring the need to monitor and manage land-use transitions carefully (Xiaoxu et al., 2024).

To create land management strategies that effectively balance urban growth and environmental sustainability, it is crucial to understand the geographic distribution of carbon stocks in rapidly developing cities. Carbon stock assessments provide critical insights into how different land uses contribute to or mitigate climate change, and they support conservation and restoration efforts. This study uses the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) Carbon Storage and Sequestration model, a widely applied tool that integrates land use/land cover (LULC) data, carbon pool estimates, and remote sensing inputs to generate spatially explicit carbon stock maps (Redhead et al., 2016). Unlike aggregate models, InVEST's pixel-based outputs enable detailed detection between different land types, including forests, mangroves, croplands, and urban green spaces. Its scenario modeling capability also provides essential decision support for urban planners and policymakers, helping prioritize areas for conservation or restoration in order to enhance carbon sequestration and align land-use decisions with climate mitigation goals Moreover, as demonstrated in a national-level analysis, regions within Indonesia exhibit varied carbon intensities and per capita emissions, highlighting the need for localized carbon management strategies (Rum et al., 2024). Parepare's characteristics, land use, socioeconomic patterns, and infrastructure, should be considered in developing its carbon storage potential. Addressing the escalating urgency of the 1.5°C and 2°C climate targets demand the widespread and scalable implementation of carbon capture and storage (CCS) technologies. Yet feasibility remains challenged by investment gaps and technological constraints (Kazlou et al., 2024). Integrating CCS into Parepare would require not only geological readiness but also institutional capacity and public support.

This study combines the InVEST model with Geographic Information Systems (GIS), satellite imagery, and global carbon density datasets to quantify carbon stocks across diverse land-use types in Parepare City. The objectives are to (1) estimate the total carbon stock using spatial modeling techniques and (2) analyze the contribution of different land uses to overall carbon storage capacity. By achieving these aims, the research enhances understanding of urban carbon dynamics in developing regions and underscores the importance of integrating natural ecosystems within urban landscapes to mitigate climate change

2. Location of Study

Parepare City is in South Sulawesi, Indonesia, situated on the western coast of Sulawesi Island in its southern arm. The city holds a strategic position approximately 150 km (93 miles) north of Makassar, the provincial capital of South Sulawesi, serving as a key regional hub that connects the northern and southern parts of the island through land transportation networks (*Regional Development Planning Agency of Parepare, No. 1*, 2021). As of mid-2023, Parepare has an estimated population of 160,309 residents, comprising 79,753 males and 80,556 females (*Central Statistics Agency of Parepare City*, 2024). The city's geographical coordinates are approximately 4°01′00″S latitude and 119°36′00″E longitude.

Figure 1. Study location (a) map of Indonesia; (b) map of Parepare City

Parepare City's tropical monsoon climate, marked by distinct wet and dry seasons, is a direct result of its coastal position. The city receives an average annual rainfall ranging from approximately 2,000 to 3,000 mm, with the wet season generally spanning from November to April (Meteorological, Climatological, and Geophysical Agency of Indonesia (*Meteorology, Climatology, and Geophysics Agency*, 2025). Given its strategic location and rapid growth, Parepare provides a valuable case study for examining carbon storage dynamics in urbanizing tropical landscapes.

3. Research Methodology

To assess carbon stocks in Parepare City (shown in figure 2), this study integrated satellite imagery analysis, GIS, and the InVEST modeling framework. SPOT 7 Satellite Imagery (2016) was selected for its high spatial resolution, enabling detailed LULC mapping. Global datasets were chosen for carbon density values to ensure consistency and comparability with other studies: the Global Aboveground and Belowground Biomass Carbon Density Maps (2010) (Spawn & Gibbs, 2020) for AGB and BGB, and the Global Soil Organic Carbon Map v1.5 (2019)(*Global Soil Organic Carbon Map v1.5 (GSOC) - "FAO Catalog,"* n.d.) for SOC. The InVEST "Carbon Storage and Sequestration" module was employed due to its capacity to spatially model and quantify ecosystem services based on biophysical data. GIS facilitated the spatial analysis and visualization of carbon stocks. Field observations and comparison with regional studies were incorporated to validate LULC classification and carbon density values, respectively, enhancing the accuracy and reliability of the results.

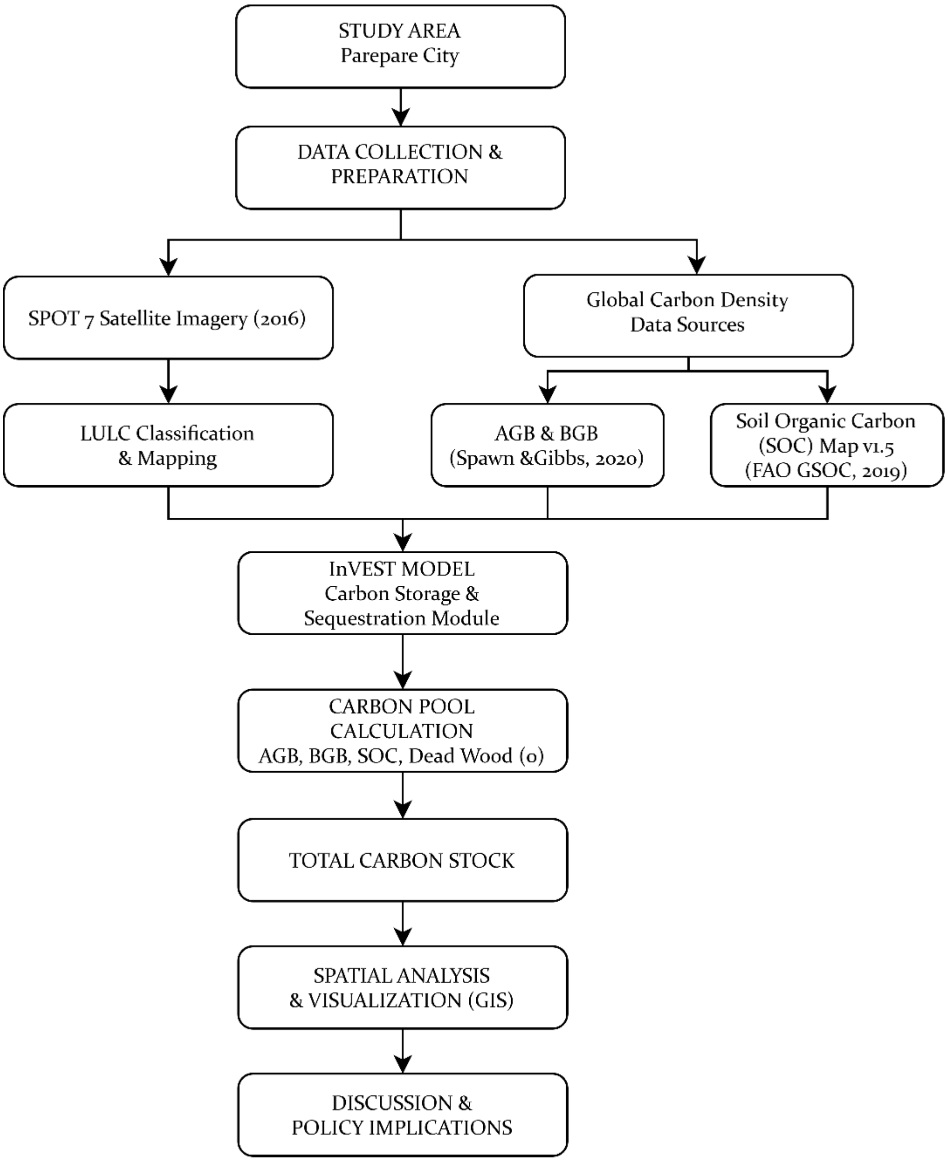


Figure 2. Overall Methodology.

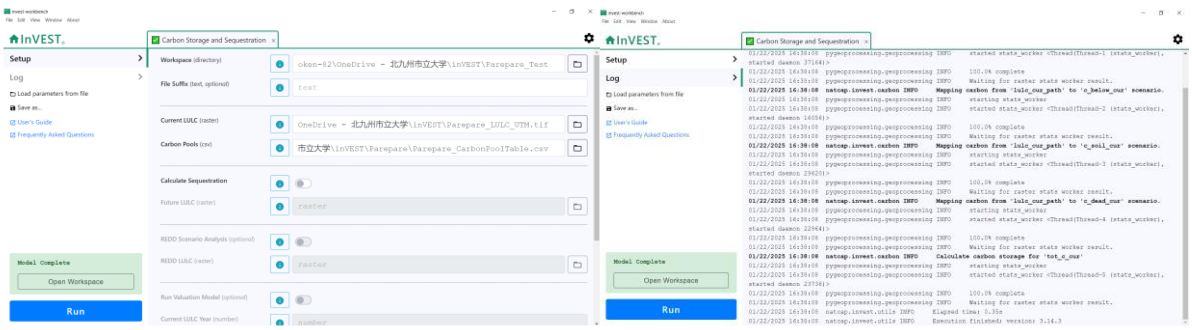


Figure 3. Run process in InVEST

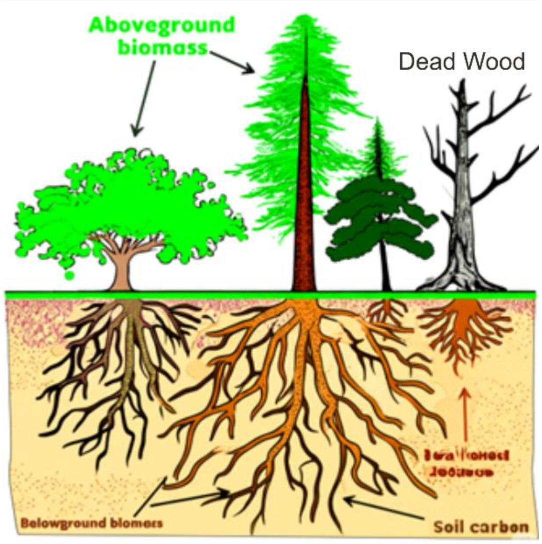


Figure 3. Carbon value sources

Figure 3 illustrates the conceptual framework of terrestrial carbon pools, including BGB, AGB, dead wood, and SOC. These components represent key carbon reservoirs within forest ecosystems. Aboveground biomass, which includes living trees and vegetation, captures atmospheric carbon through photosynthesis, while belowground biomass contributes to long-term carbon storage through root systems. Additionally, dead wood and litter serve as intermediate carbon pools, gradually decomposing and enriching carbon soil. However, the limitations of this research do not include dead wood data where there are limitations in data sources that must be carried out through direct surveys. Soils contain more than two-thirds of terrestrial carbon reserves, making them vital in mitigating GHG emissions. Despite challenges in quantifying and verifying long-term sequestration, soil remains a major carbon sink in climate strategies (Rodrigues et al., 2023).

4. Research and Discussion

4.1. Visualizing Parepare City's LULC Dynamics

The carbon stock analysis of Parepare City commences with a depiction of the research area boundaries, delineated in red on the 2016 SPOT 7 satellite imagery, as shown in Figure 4 (a). In figure 4 (b), the map delineates various land cover types, including settlement areas, wastelands, agricultural lands, fields, farms, shrubs, fishponds, infrastructure, mixed forests, mining areas, sand beaches, and rivers. These LULC classes were identified based on visual interpretation and primary survey data, following standard remote sensing classification techniques. The spatial distribution of these LULC types significantly influences the overall carbon storage capacity of the city, as different land covers have varying capacities to store carbon in their biomass and soil. The use of a 2016 LULC map provides a snapshot of land cover distribution at that time, which is valuable for understanding the baseline carbon storage potential. Table 1 presents the LULC statistics for Parepare City.

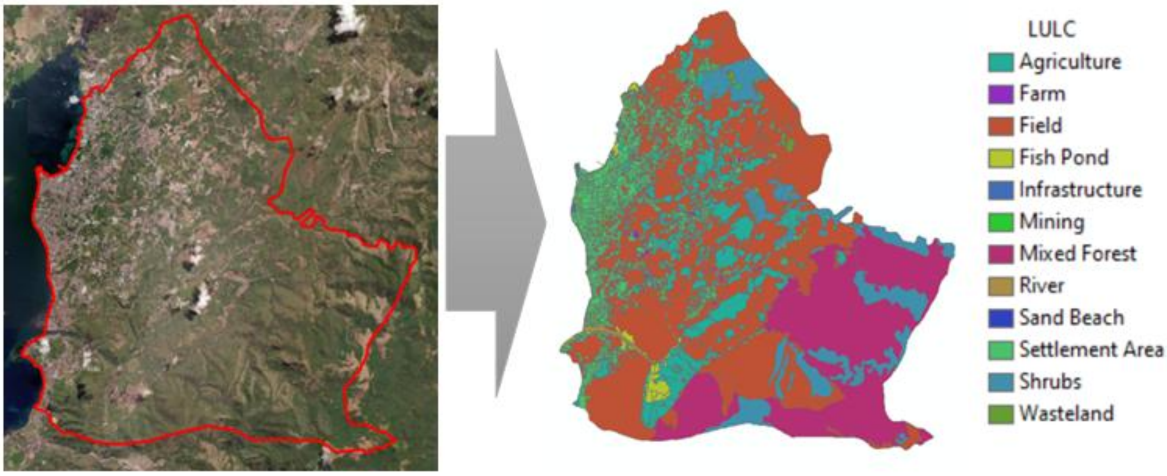


Figure 4. (a) SPOT 7 satellite image 2016, (b) LULC map of Parepare City

Table 1. LULC statistic of Pare-Pare City

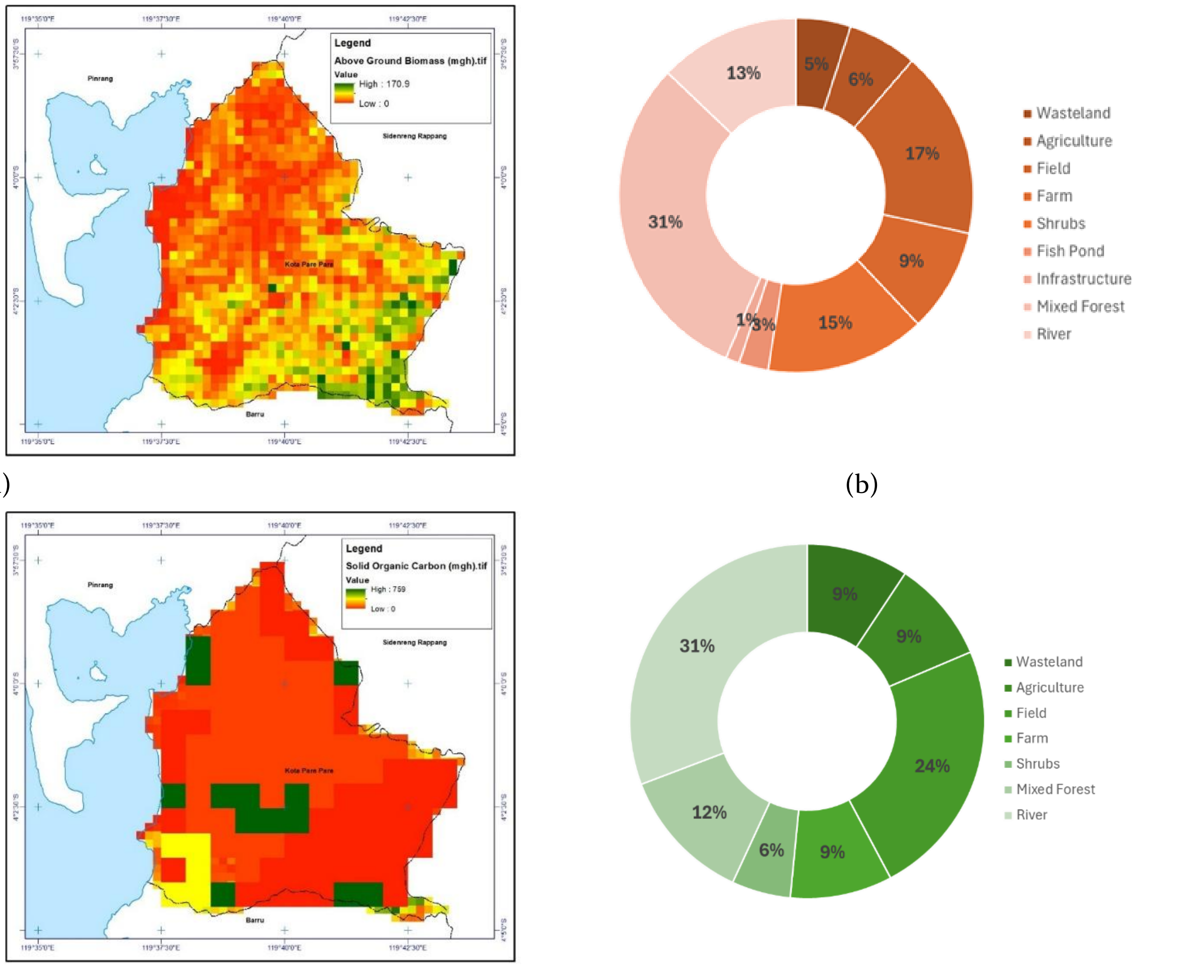
No.	Classes	Area (hectare)	Area (%)
1	Agriculture	1,013.15	10.23%
2	Farm	22.30	0.23%
3	Field	4,289.86	43.34%
4	Fishpond	95.55	0.97%
5	Infrastructure	14.84	0.15%
6	Mining	5.79	0.06%
7	Mixed Forest	2,135.85	21.58%
8	River	79.29	0.80%
9	Sand Beach	0.98	0.01%
10	Settlement Area	1,217.41	12.30%
11	Shrubs	858.14	8.67%
12	Wasteland	166.05	1.68%
Grand Total		**9,899.22**	**100.00%**

Based on Table 1, the total land area analyzed is 9,899.22 hectares, distributed across various LULC classes. The largest portion of land is classified as field, occupying 4,289.86 hectares or 43.34% of the total area. This is followed by mixed forest, which covers 2,135.85 hectares or 21.58%. Built-up areas, specifically settlements, account for 1,217.41 hectares, making up 12.30% of the landscape. Water bodies include fishponds, occupying 95.55 hectares (0.97%), and rivers occupying 79.29 hectares (0.80%). Shrub areas cover 858.14 hectares (8.67%). The smallest land category is sand beach, which comprises only 0.98 hectares or 0.01% of the total area. This classification highlights the dominance of natural and semi-natural land uses, particularly field and mixed forest areas, suggesting a landscape with substantial ecological and productive functions.

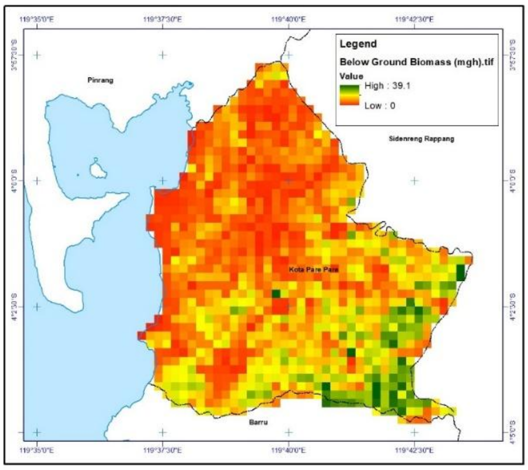
The InVEST model calculates the carbon stored in each pixel based on the LULC classification and associated carbon values, then sums these values across the urban landscape. Consequently, the spatial distribution of different land cover types in Parepare City directly determines the location and extent of this stored carbon.

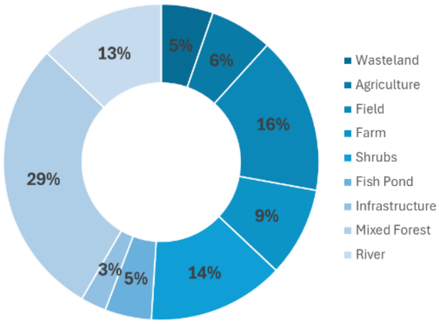
4.2. Carbon Stock Assessment

To quantify carbon stocks in Parepare City, this study utilized spatial analysis integrating LULC classification with carbon density values processed using the InVEST model. The maps display spatial distributions of carbon pools, including AGB, BGB, SOC, across different LULC classes. A total of 12 land cover categories were identified, each assigned specific carbon values (in Mg C/ha) corresponding to these three carbon pools. The Mixed Forest category exhibits the highest carbon density, reflecting its critical role in urban carbon storage. Similarly, River areas demonstrate significant carbon storage, especially in soils, likely due to sediment accumulation and organic-rich substrates. In contrast, Settlement Areas, Infrastructure, and other categories recorded zero values across all carbon pools, indicating highly impervious and developed surfaces. Moderate carbon values were observed in Shrubs, Farm, and Field categories, which combine vegetation and soil carbon components. The integration of spatial land cover mapping with carbon stock coefficients provides a robust framework for assessing and visualizing urban ecosystem carbon storage, highlighting the importance of preserving natural and semi-natural land covers in urban planning and climate mitigation strategies.



(a) (b) (c) (d)





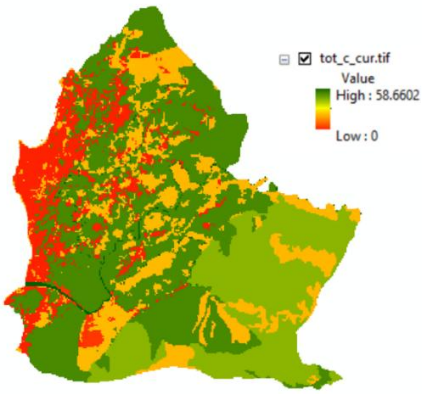
(e) (f)

Figure 5. (a) Aboveground Biomass (AGB), (b) AGB pie chart, (c) Soil Organic Carbon (SOC), (d) SOC pie chart, (e) Belowground Biomass (BGB), (f) BGB pie chart (Mg C/ha)

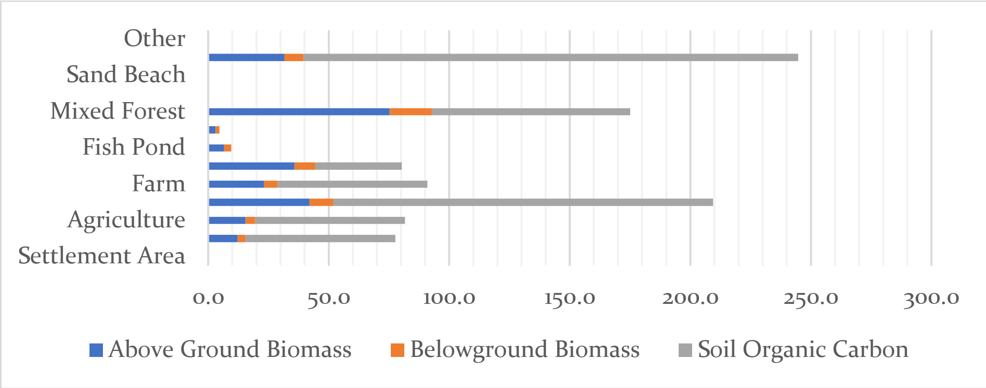
Figure 5 illustrates the spatial distribution of key carbon pools within Parepare City, including AGB, SOC, and BGB. Specifically, Figure 5 (a) AGB, showing areas with higher vegetation density in greener tones and areas with lower biomass in red and yellow. Figure 5 (c) represents the distribution of SOC, highlighting areas with rich organic soils in darker green, while urbanized or barren areas show lower SOC values. Figure 5 (e) displays the BGB, indicating the carbon stored in root systems, with similar spatial patterns to AGB as they are intrinsically linked. The accompanying donut charts visually represent the proportional contribution of different LULC categories to each carbon pool. For instance, Figure 5 (b) shows the percentage contribution of various LULC types to AGB, Figure 5 (d) for SOC, and Figure 5 (f) for BGB.

4.3. Assessing Carbon Sequestration Patterns

The spatial distribution of carbon storage within Parepare City was mapped using GIS software, integrating the carbon stock assessment results from the InVEST model. This map provides a visual representation of the spatial patterns of carbon storage, highlighting areas with high and low carbon sequestration potential.



(a)



(b)

Figure 6. (a) The carbon storage map of Parepare City (Mg C/ha), (b) overall AGB, BGB, and SOC

Figure 6 presents the Carbon Storage Map of Parepare City, visually depicting the spatial distribution of estimated carbon stocks across its landscape. The map uses a color gradient to indicate varying levels of carbon storage, ranging from "Low: 0" to "High: 58.6602" Mg C/ha. Areas represented by darker green tones indicate higher concentrations of stored carbon, typically corresponding to denser vegetation cover such as mixed forests and certain agricultural lands. These areas function as important carbon sinks, playing a crucial role in regulating local and regional carbon cycles. Conversely, urbanized areas, barren lands, and infrastructure (represented by red and orange hues) exhibit lower or zero carbon storage potential, highlighting the impact of human development and lack of vegetation. The calculated current carbon storage and sequestration for Parepare City is 1,456,909.41 Mg C. This spatial variability underscores the critical importance of land use planning and conservation efforts in maximizing carbon sequestration within Parepare City. By identifying priority areas for conservation, urban greening, and land restoration, the map offers valuable insights for boosting the city's carbon sequestration and helping to lessen the effects of climate change.

Table 2. Carbon storage in urban vegetation in various cities/countries

No	City / Country	Carbon Stock (Mg C)	Area (ha)	Carbon Density (tC/ha)	References
1	Parepare, Indonesia	1,456,909.41	9,899.22	147.2	Result of this study (2024, using InVEST + SPOT 7 imagery)
2	Hangzhou, China	11,740,000	169,000	69.5	(Zhao et al., 2010)
3	Tehran, Iran	~256,800	59,565	4.31	(Rasoolzadeh et al., 2024)
4	Kathmandu, Nepal	~215,850	3,950	54.6	(Ugle et al., 2010)
5	New York City, USA	1,860,000	7,060	263.5	(Intergovernmental Panel On Climate Change (Ipcc), 2023)
6	Atlanta, USA	~5,360,000	150,000	35.7	(*Appendix A*, 2022)
7	London (Camden), UK	~194,000	~3,880	~50	(Disney, 2018)
8	Baltimore, USA	~2,724,800	~108,000	25.28	(Sharma et al., 2024)

No	City / Country	Carbon Stock (Mg C)	Area (ha)	Carbon Density (tC/ha)	References
9	Boston, USA	~355,000	~12,300	28.8	(Raciti et al., 2014)
10	Kumasi, Ghana	~1,110,000	~10,000	111	(Sharma et al., 2024)
11	Beijing, China	~1,278,000	~29,240	43.7	(Sharma et al., 2024)
12	Shenyang, China	~1,662,000	~50,000	33.22	(Sharma et al., 2024)
13	Barcelona, Spain	~268,800	~24,000	11.2	(Sharma et al., 2024)

Parepare City stands out with one of the highest carbon densities among the listed urban areas, reaching approximately 147.2 tons of carbon per hectare (tC/ha). This value is significantly higher than that of cities like Hangzhou, China, or Kumasi, Ghana, which are also known for their green cover. The high carbon density in Parepare may reflect a combination of factors, including a relatively high proportion of vegetated or forested areas, the inclusion of multiple carbon pools such as soil and litter in the assessment, and potentially lower levels of impervious surfaces like roads and buildings. Among the cities compared, only New York City reports a higher carbon density, at around 263.5 tC/ha, but this figure specifically pertains to forested natural areas rather than the city. This highlights Parepare's strong potential for carbon storage within its urban landscape.

Urban carbon footprints are closely linked to land conversion and infrastructure development. Ranchi, India, for instance, experienced rapid land-use transformation that led to significant reductions in vegetative carbon sinks, mirroring potential risks in Parepare if urban sprawl is not managed (Kumar & Kumar, 2019). Meanwhile, studies on urban parks in Lima, Peru, demonstrated that even ornamental trees like *Ficus benjamina* can significantly contribute to carbon sequestration and oxygen production, supporting the role of planned green spaces in enhancing urban resilience (Aguilar-Tello et al., 2023). Similarly, from the aviation sector, (Baxter, 2020) highlighted that decarbonization strategies—even in high-emission industries, benefit greatly from structural and operational innovations. In urban contexts, such insights underline the need for city planning that favors energy-efficient transport, renewable infrastructure, and robust green zones to collectively reduce carbon footprints.

Developing countries now bear a greater share of CO_2 emissions responsibilities, both from domestic production and participation in global value chains. This trend underscores the need for more inclusive climate accountability mechanisms (Chen et al., 2022).

4.4. Relevance for Land Use and Climate Action

Forests and field areas in Parepare recorded the highest levels of carbon storage, emphasizing the ecological significance of these areas in urban contexts. These results align with findings from other urban studies, where vegetation-rich zones have proven crucial for mitigating greenhouse gas emissions (Aguilar-Tello et al., 2023). The findings of this study offer crucial insights for urban planning and climate change mitigation strategies within Parepare City. By pinpointing key carbon sequestration zones such as mixed forests and agricultural areas, the research underscores the critical need for robust conservation efforts and sustainable land management. Given Indonesia's standing as a leading global greenhouse gas emitter, this research can serve as a foundational step for Parepare to develop targeted policies for land use management and effective climate change mitigation.

The insights gained here can effectively inform land use planning decisions, helping to strategically allocate conservation resources and encourage sustainable practices in areas rich in carbon sequestration potential. For example, reforestation and afforestation projects can be targeted in areas with degraded or deforested land to enhance carbon sequestration. In addition to natural carbon sinks, the built environment can play a significant role in carbon storage using biogenic construction materials such as harvested wood products or materials capable of carbonation. This concept, known as "buildings as a carbon sink," highlights the potential for storing atmospheric carbon over long timescales in urban infrastructure (Arehart et al., 2021). In the context of Parepare, integrating carbon-storing materials in urban planning could enhance overall carbon sequestration efforts.

This study points to a clear need for protecting and restoring natural ecosystems as a primary means of enhancing carbon sequestration. In parallel, encouraging sustainable agricultural practices, including agroforestry and conservation tillage, can be a powerful tool for increasing the carbon stored in farmlands (cite source). Urban planning strategies should prioritize the preservation of green spaces and the integration of vegetation into urban landscapes to enhance carbon sequestration in urban areas. This approach is consistent with the tenets of sustainable urban development, ultimately enhancing the quality of life for city residents.

4.5. Limitation of Study

This study, however, comes with several limitations that warrant acknowledgment. The carbon values for each (LULC) type were derived from global datasets. For more precise assessments of carbon stock, future research ought to prioritize gathering local data on carbon stocks across diverse LULC categories. In addition, it is necessary to add deadwood value through direct surveys to complete the carbon pool input data. Future research could also explore the potential impacts of climate change on carbon storage in Parepare City. By assessing how various land types are impacted by climate change, specifically through events like coastal inundation and extreme weather, we can develop more effective adaptation strategies and strengthen carbon sequestration efforts. This could involve modeling the potential impacts of climate change scenarios on carbon stocks and identifying areas that are most vulnerable to carbon loss.

5. Conclusion

This study successfully quantified the total carbon stock in Parepare City, Indonesia, at approximately. 1,456,909.41 Mg C using the InVEST model and GIS techniques. The spatial analysis robustly identified mixed forests, fields, and shrubs as critical land use/land cover types significantly contributing to the city's carbon storage capacity. These findings are particularly salient given Parepare City's unique position: unlike many rapidly urbanizing areas in Indonesia, it has largely retained its natural carbon stocks, positioning it as a vital proactive case study for effective urban planning and combating the effects of climate change.

The sustained high carbon density within Parepare, notable even among other global cities, underscores the profound importance of its existing natural ecosystems as carbon sinks. This research provides crucial, spatially explicit insights that directly inform climate-responsive land management. It highlights an urgent need for policies that prioritize forest conservation, urban greening initiatives, and the promotion of eco-friendly farming methods, such as integrating trees into farming systems and minimizing soil disturbance, to boost the local area's carbon storage capacity and support Indonesia's broader climate change mitigation targets.

Ultimately, this study offers a foundational tool for urban planners and policymakers in Parepare City, enabling data-driven decisions that balance urban growth with essential ecosystem conservation for a sustainable future. Future research should build upon this assessment by incorporating local carbon density data to refine accuracy, analyzing land cover changes over time to understand carbon dynamics, and assessing the vulnerability of these carbon stocks to projected climate change impacts, thereby enhancing the city's resilience.

Acknowledgment
Sincere gratitude is extended to the Matsumoto Laboratory at the University of Kitakyushu, whose invaluable support and guidance were essential to the successful completion of this research. Special thanks are extended to the Parepare City Government and the Regional Planning Agency for providing access to essential data and resources for this research. The author also gratefully acknowledges the contributions of other parties who assisted with data collection, analysis, and manuscript preparation. Without their help, this would not be possible.

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