doi: 10.37905/jgeosrev.v8i2.37098 ejurnal.ung.ac.id/index.php/jgeosrev

Vol. 8, No. 2, July 2026: 211-220

Jambura Geoscience Review

p-ISSN 2623-0682 | e-ISSN 2656-0380

Department of Earth Science and Technology, Universitas Negeri Gorontalo

Estimating Carbon Stock from Land Cover Dynamics Using Stock-Difference in Gunungpati

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ARTICLE INFO

Article history:
Received: 23 January 2026
Accepted: 20 June 2026
Published: 03 July 2026

Keywords:
AGB; Carbon Stock; Land Cover Change; Stock-Difference

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ABSTRACT

Changes in land use in peri-urban areas directly affect vegetation structure and aboveground biomass carbon stocks, particularly in landscapes experiencing rapid settlement expansion. This study aimed to identify spatial and temporal patterns of land use change, estimate aboveground biomass carbon stocks for each land use class, and quantify the rate of carbon stock change in the Gunungpati District, Semarang City, from 2014 to 2024. Multi-temporal Landsat 8 imagery from 2014, 2019, and 2024 were classified into eight land use classes using supervised classification with the maximum likelihood algorithm. Carbon stocks were estimated by multiplying the area of each land use class by its carbon stock coefficient, while temporal carbon stock changes were quantified using the stock difference method. The results showed substantial land use transformation, marked by a sharp decrease in dryland agriculture, the dominance of mixed dryland agriculture, and continuous settlement expansion. Total carbon stock increased from 137,404.12 tons C in 2014 to 268,488.02 tons C in 2019, before declining to 240,020.17 tons C in 2024. The annual carbon-stock change was 26,216.78 tons C/year during 2014–2019, −5,693.57 tons C/year during 2019–2024, and 10,261.61 tons C/year during 2014–2024. These findings indicate that the Gunungpati District retained a net carbon stock gain over the study period; however, the post-2019 decline suggests increasing ecological pressure from settlement expansion. Protecting vegetation-based land covers is therefore essential to maintain the district's role as a green open space reserve and to support climate change mitigation.

How to cite: Pangestu, A. (2026). Article title. *Estimating Carbon Stock from Land Cover Dynamics Using Stock-Difference in Gunungpati, 8* (2), 211-220. https://doi.org/10.37905/jgeosrev.v8i2.37098

1. INTRODUCTION

Land use and land cover change are among the main drivers of alterations in terrestrial carbon stocks. This process directly modifies vegetation structure, biomass accumulation, and the capacity of landscapes to function as carbon sinks (Schimel et al., 2015; Seto et al., 2012). The conversion of vegetated land into settlements, open land, and other intensive land uses reduces aboveground biomass and may weaken the ecological role of peri-urban landscapes in climate regulation (Tao et al., 2015; Zhang et al., 2020). In rapidly urbanizing regions, this issue becomes more critical because development pressure often occurs in areas that retain important ecological functions, including agricultural land, mixed vegetation, and green open spaces (Shao et al., 2023).

Semarang City represents an important case of urban ecological transition in Indonesia. Population growth, infrastructure development, and settlement expansion have increased pressure on the remaining vegetated areas in this city (Novianti et al., 2024). The Gunungpati District has strategic ecological significance because it functions as a protected area and a reserve for green open spaces within the spatial planning framework of Semarang City (PERDA Kota Semarang, 2021). However, its position in the urban fringe also makes it vulnerable to gradual land conversion, particularly because previous studies have reported continued spatial transformation in this district (Kusrini, 2021; Anggraeni et al., 2023).

Previous studies have demonstrated that land conversion generally reduces carbon storage capacity. The conversion of forests, plantations, agricultural land, or mixed vegetation into built-up areas replaces vegetation biomass with surfaces that have lower carbon density (Fadhli et al., 2021; Permata & Rahayu, 2021). Similar patterns have also been reported in mangrove and peatland ecosystems, where declining vegetation cover and land degradation reduce ecosystem carbon stocks (Husna et al., 2019; Rifandi, 2021; Septian et al., 2023). At the national level, this issue is closely related to Indonesia's climate-mitigation agenda, particularly the Enhanced Nationally Determined Contribution and the Forest and Other Land Use Net Sink 2030 target, which emphasize the importance of maintaining and increasing vegetation-based carbon stocks (KLHK, 2022; Republic of Indonesia, 2022).

Urban and peri-urban landscapes have been insufficiently examined in carbon-stock studies. Most carbon-stock assessments in Indonesia have focused on natural ecosystems, protected forests, peatlands, plantations, or mangrove areas (Karuru et al., 2020; Rifandi, 2021; Septian et al., 2023). In contrast, peri-urban areas experience intense land conversion and play an increasingly important role in spatial planning, green open space provision, and climate adaptation. Existing urban studies commonly emphasize land-cover mapping without explicitly linking land-cover transitions to above-ground biomass carbon-stock dynamics (Novianti et al., 2024). This condition creates a research gap in explaining how incremental land conversion in urban fringe areas affects temporal carbon-stock patterns.

The stock difference method provides a relevant framework for evaluating temporal changes in carbon stocks. This method estimates the difference in carbon stocks between two observation periods and is recommended for carbon stock accounting (IPCC, 2006). It is suitable for multi-temporal land-cover analysis because each land-cover class can be assigned a carbon-stock coefficient, allowing changes in class area to be translated into estimated changes in aboveground biomass carbon (FAO, 2014; Röhling et al., 2016). When combined with satellite-based land cover classification, this approach enables a spatially explicit assessment of carbon stock dynamics across different observation years.

This study addresses this identified gap by integrating multi-temporal Landsat 8 land-cover classification with stock-difference-based carbon-stock estimation. The analysis focuses on the Gunungpati District for 2014, 2019, and 2024. The novelty of this study lies in its explicit linkage between land-cover transition matrices and above-ground biomass carbon-stock estimation in a peri-urban landscape that functions as a green open-space reserve. Accordingly, this study aims to: (1) identify spatial and temporal patterns of land-cover change in the Gunungpati District; (2) estimate above-ground biomass carbon stocks for each land-cover class; and (3) quantify the rate of carbon-stock change during 2014–2019, 2019–2024, and 2014–2024.

2. METHOD

2.1. Research Location and Procedure

This study was conducted in the Gunungpati District, Semarang City. Administratively, Gunungpati District comprises 16 sub-districts, namely, Pakintelan, Mangunsari, Plalangan, Gunungpati, Nongkosawit, Pongangan, Ngijo, Patemon, Sekaran, Sukorejo, Sadeng, Cepoko, Sumurrejo, Jatirejo, Kalisegoro, and Kandri (BPS Kota Semarang, 2024). Gunungpati District was selected as the study area because it functions as a protected area and a reserve for green open spaces in Semarang City. However, this area has experienced rapid development and land conversion, which may affect its ecological conditions, particularly its capacity to store aboveground biomass carbon.

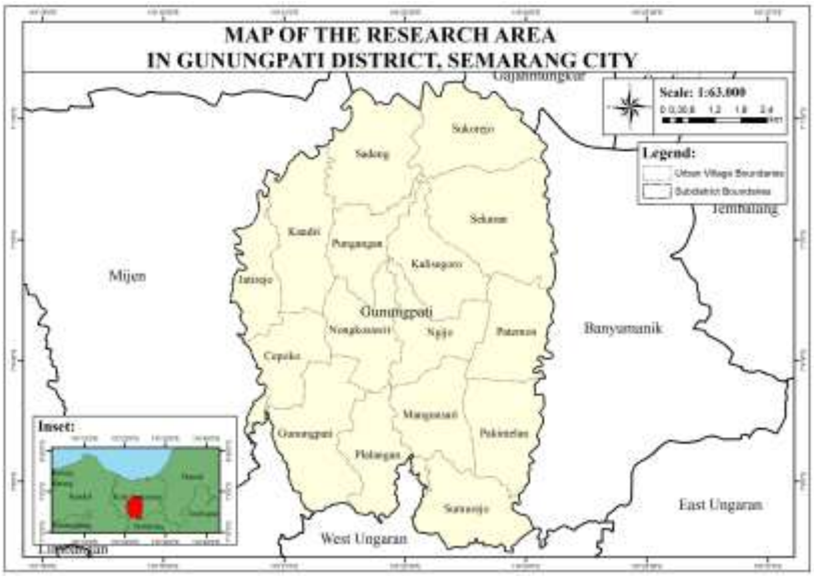

Figure 1. Map of the research location

The study consisted of five main stages (Figure 2): data collection, image preprocessing, land-cover classification, accuracy assessment, and carbon-stock estimation. The data included Landsat 8 imagery Path 120/Row 065 for 2014, 2019, and 2024 with cloud cover below 10%, administrative boundaries, field validation data, and carbon-stock coefficients from the Ministry of Environment and Forestry and Indonesia's Second Forest Reference Level. Image preprocessing was conducted in ArcGIS 10.7.1 through radiometric and geometric correction, cloud–shadow masking, and subsetting based on the Gunungpati District boundary. Land-cover classification used supervised maximum likelihood classification with eight classes: plantation forest, plantations, settlements, open land, water bodies, dryland agriculture, mixed dryland agriculture, and rice fields. Accuracy assessment was performed using a confusion matrix based on 48 stratified random reference points from GPS-based field validation and Google Earth imagery. Finally, above-ground biomass carbon stock was estimated by multiplying the area of each land-cover class by its carbon-stock coefficient, while temporal changes were calculated using the stock-difference method.

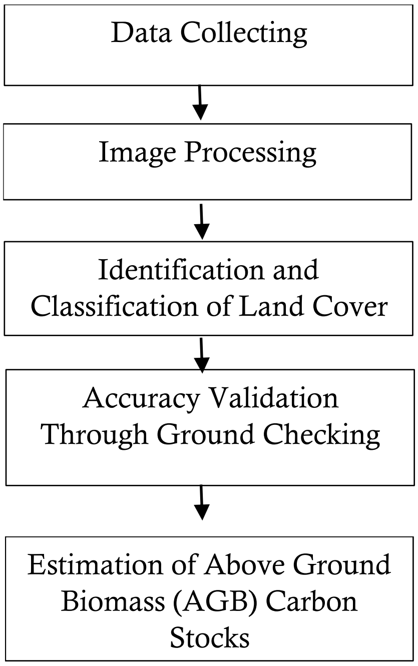

Figure 2. Research method flowchart

2.2. Data and Data Source

The data used in this study consisted of primary and secondary data. Primary data were obtained through field ground checking, including sample coordinates for classification validation, direct observation of land cover conditions, and visual documentation. Field validation was supported by Avenza Maps to record and verify the ground reference points.

Secondary data included Landsat 8 satellite imagery from 2014, 2019, and 2024 acquired from the United States Geological Survey EarthExplorer, administrative boundary shapefiles from Indonesian Geospasial, and carbon-stock coefficient data from Indonesia's Second Forest Reference Level. Additional supporting references included the Intergovernmental Panel on Climate Change guidelines and Ministry of Environment and Forestry documents related to national forest reference levels and carbon-stock estimation.

2.3. Carbon Stock Analysis

Carbon stock was estimated by multiplying the area of each land-cover class by its corresponding carbon-stock coefficient, expressed in metric tons C/ha, as presented in Table 2. The coefficients used in this study were derived from biomass estimates in Indonesia's Second Forest Reference Level (KLHK, 2015). Biomass values were converted into carbon stocks using a carbon fraction of 0.47, indicating that one metric ton of dry biomass is equivalent to 0.47 tons of carbon.

Table 1. Carbon stock coefficients for each land-cover class

No.	Land Cover Type	AGB (ton/ha)	Carbon Stock Coefficient (tonC/ha)	Source
1	Plantation Forest (HT)	161,23	75,78	Indonesia 2nd FRL, 2022
2	Plantation (Pk)	102,35	48,10	Indonesia 2nd FRL, 2022
3	Settlements (Pm)	4,61	2,17	Indonesia 2nd FRL, 2022
4	Open Land (T)	5,11	2,40	Indonesia 2nd FRL, 2022
5	Water Body (A)	0	0	Indonesia 2nd FRL, 2022
6	Dryland Agriculture (Pt)	29,95	14,08	Indonesia 2nd FRL, 2022
7	Mixed Dryland Farming (Pc)	137,52	64,63	Indonesia 2nd FRL, 2022
8	Rice Fields (Sw)	21,27	10,00	Indonesia 2nd FRL, 2022

The total carbon stock for each observation year was calculated using the following equation:

$$C_t = \Sigma(A_i \times C_i) \qquad (1)$$

where C_t is the total carbon stock in year t (ton C), $A_i$is the area of land-cover class i (ha), and C_i is the carbon-stock coefficient of land-cover class i (ton C/ha).

2.4. Analysis of Changes in Carbon Stocks

Changes in carbon stocks resulting from land-cover change were calculated using the stock-difference method. This approach compares estimated carbon stocks between the initial and final observation years. The method is appropriate for multi-temporal land-cover analysis because each land-cover class is assigned a specific carbon-stock coefficient, allowing changes in land-cover area to be translated into changes in carbon stocks.

The annual rate of change in carbon stocks was calculated by dividing the difference in carbon stocks between two observation years by the time interval. The calculation was performed for three periods: 2014–2019, 2019–2024, and 2014–2024. The equation used is as follows:

$$\Delta C = \frac{(Ct2 - Ct1)}{(t2 - t1)} \quad (2)$$

where ΔC is the annual change in carbon stock in each pool (tC/year), t_1 is the initial year of the pool, t_2 is the final year of the pool, Ct_1 is the carbon stock at the initial time (tC), and Ct_2 is the carbon stock at the final time (tC).

3. RESULTS AND DISCUSSION

3.1. Spatial and Temporal Patterns of Land-Cover Change

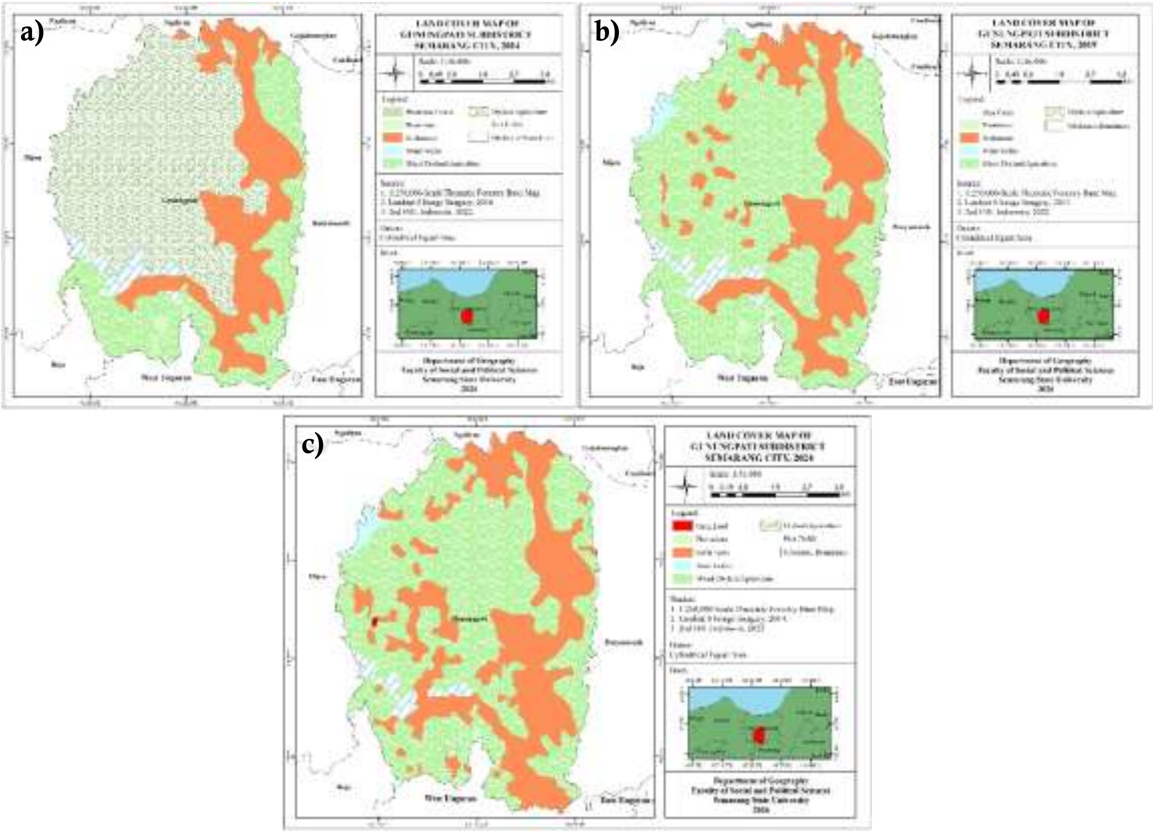

Figure 3. a) Interpretation of Land Cover in 2014, b) Interpretation of Land Cover in 2019, c) Interpretation of Land Cover in 2024

Land cover change in the Gunungpati district shows a clear spatial and temporal transformation during 2014–2024. The interpretation results indicate that the study area experienced substantial changes in the proportions of agricultural, vegetated, and built-up land cover classes.

Table 2. Land Cover Area in Gunungpati District 2014, 2019, and 2024 (ha)

Land Cover	Land Cover Area (ha)		
	2014	2019	2024
Plantation Forest	0,49	-	-
Plantations	37,09	36,72	17,50
Settlements	1.344,63	1.651,86	2.134,29
Open Land	-	-	3,67
Water bodies	5,19	66,17	66,17
Dryland Agriculture	3.059,77	0,67	16,05
Mixed Dryland Agriculture	1.359,41	4.043,41	3.604,22
Rice fields	172,48	180,23	137,15
Total	5.979,06	5.979,06	5.979,06

In 2014, dryland agriculture was the dominant land cover class, covering 3,059.77 ha, or 51.15% of the total study area. Mixed dryland agriculture covered 1,359.41 ha, whereas settlements occupied 1,344.62 ha. This pattern indicates that the Gunungpati district was largely characterized by agricultural and vegetated land covers at the beginning of the observation period. By 2019, mixed dryland agriculture increased substantially to 4,043.41 ha (67.61 %), whereas dryland agriculture decreased sharply to only 0.67 ha. In 2024, mixed dryland agriculture remained the dominant land cover class, although its area decreased to 3,604.22 ha. In contrast, settlements continued to expand, reaching 2,134.29 ha.

Table 3. Changes in Land Cover Area in Gunungpati District from 2014, 2019, and 2024 (ha)

Land Cover	Changes in Land Cover Area (ha)		
	2014-2019	2019-2024	2014-2024
Plantation Forest	-0,49	0,00	-0,49
Plantations	-0,37	-19,22	-19,59
Settlements	307,23	482,43	789,67
Open Land	0,00	3,67	3,67
Water bodies	60,98	0,00	60,98
Dryland Agriculture	-3.059,10	15,38	-3.043,72
Mixed Dryland Agriculture	2.684,00	-439,19	2.244,80
Rice fields	7,75	-43,08	-35,32
Total	0,00	0,00	0,00

The magnitude of land-cover change confirms that the Gunungpati district experienced a major redistribution of land-cover classes. Between 2014 and 2019, dryland agriculture decreased by 3,059.10 ha, whereas mixed dryland agriculture increased by 2,684.00 ha and Settlements increased by 307.23 ha. Between 2019 and 2024, settlement expansion became more pronounced, increasing by 482.43 ha, while mixed dryland agriculture decreased by 439.19 ha. Over the full 2014–2024 period, dryland agriculture decreased by 3,043.72 ha, whereas mixed dryland agriculture and settlements increased by 2,244.80 ha and 789.67 ha, respectively.

Table 4. Land Change Matrix for Gunungpati District in 2014, 2019, and 2024

2014/2024	Plantation Forest	Plantations	Settlements	Open Land	Water bodies	Dryland Agriculture	Mixed Dryland Agriculture	Rice fields	Total (ha)
Plantation Forest	-	0,49	-	-	-	-	-	-	0,49
Plantations	-	13,70	-	-	-	15,70	7,70	-	37,09
Settlements	-	-	1.324,25	-	-	-	20,37	-	1.344,63
Open Land	-	-	-	-	-	-	-	-	-
Water bodies	-	-	-	-	5,19	-	-	-	5,19
Dryland Agriculture	-	-	572,85	3,67	60,98	-	2.414,52	7,75	3.059,77
Mixed Dryland Agriculture	-	3,32	191,12	-	-	0,35	1.161,63	2,99	1.359,41
Rice fields	-	-	46,07	-	-	-	-	126,41	172,48
Total (ha)	**-**	**17,50**	**2.134,29**	**3,67**	**66,17**	**16,05**	**3.604,22**	**137,15**	**5.979,06**

The land-change matrix further shows that the largest transition occurred from dryland to mixed dryland agriculture. This transition explains the sharp decline in dryland agriculture and the marked expansion of mixed dryland agriculture between 2014 and 2019. However, this result should be interpreted cautiously because both classes may have similar spectral characteristics in Landsat imagery, particularly in heterogeneous peri-urban landscapes. Similar classification challenges have been reported in land-cover studies using medium-resolution satellite imagery, especially in areas with agricultural land, mixed vegetation, and fragmented built-up areas within the same landscape unit (Novianti et al., 2024; Shao et al., 2023).

The continued expansion of settlements reflects increasing pressure for urban development in the Gunungpati district. This pattern is consistent with previous studies, which have shown that peri-urban areas commonly experience a gradual conversion of agricultural and vegetated land into built-up areas as a consequence of population growth, infrastructure development, and urban expansion (Seto et al., 2012; Kusrini, 2021; Anggraeni et al., 2023). In the context of Semarang City, this finding is important because the Gunungpati district has a strategic role as a protected area and green open space reserve. Therefore, the observed changes in land cover indicate a potential conflict between ecological conservation functions and urban development needs.

3.2. Above-Ground Biomass Carbon Stock Based on Land-Cover Class

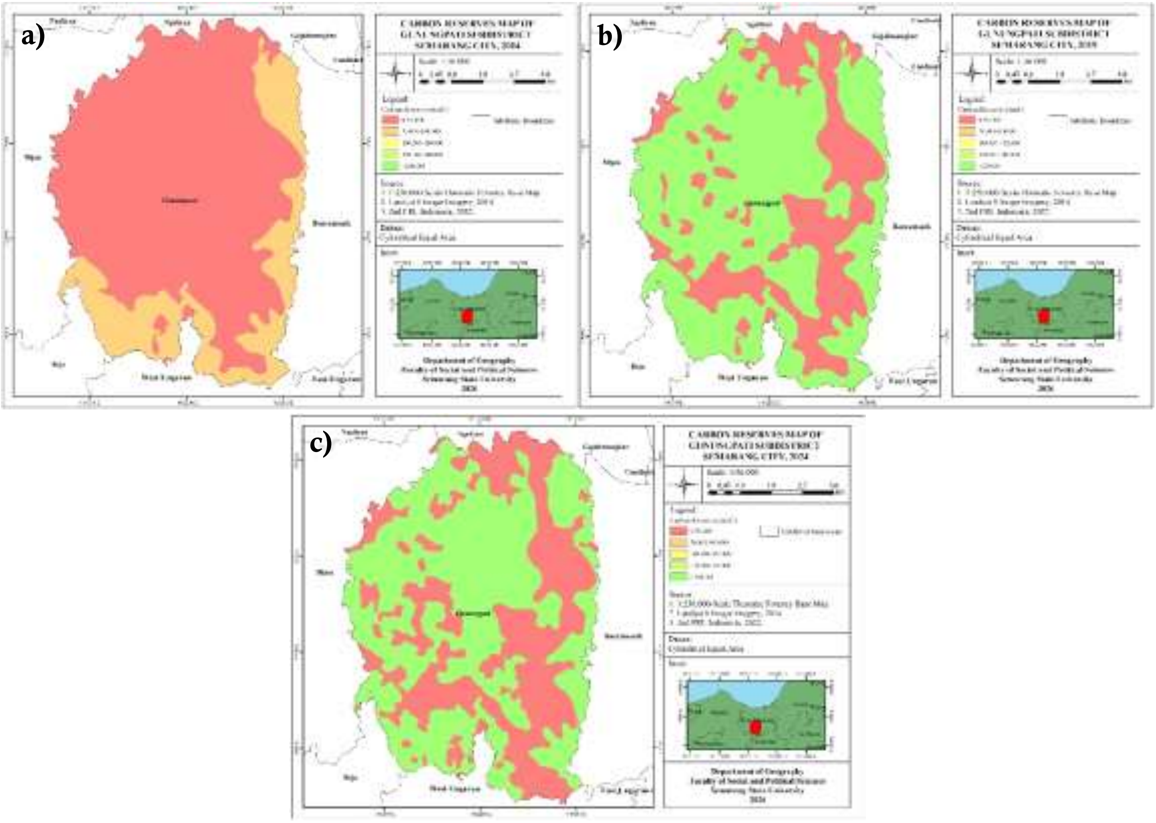

Figure 4. a) Carbon Reserves in 2014, b) Carbon Reserves in 2019, c) Carbon Reserves in 2024

The aboveground biomass carbon stock in the Gunungpati district varied according to the land-cover composition in each observation year. Because each land-cover class has a different carbon-stock coefficient, changes in the extent of each class directly influence the estimated total carbon stock.

Table 5. Carbon Reserves in Gunungpati District in 2014, 2019, and 2024 (tons of C)

Land Cover	Carbon Stock		
	2014	2019	2024
Plantation Forest	36,92	-	-
Plantations	1.784,16	1.766,19	841,93
Settlements	2.917,84	3.584,54	4.631,41
Open Land	-	-	8,81
Water bodies	-	-	-
Dryland Agriculture	43.081,56	9,37	225,93
Mixed Dryland Agriculture	87.858,89	261.325,62	232.940,56
Rice fields	1.724,75	1.802,29	1.371,53
Total	137.404,12	268.488,02	240.020,17

The estimated total carbon stock was 137,404.12 tons C in 2014. This value increased substantially to 268,488.02 tons C in 2019 and then decreased to 240,020.17 tons C in 2024. The increase from 2014 to 2019 was mainly associated with the expansion of mixed dryland agriculture, which contributed substantially to total carbon storage due to its relatively higher carbon-stock coefficient. In contrast, the decrease from 2019 to 2024 was associated with a reduction in mixed dryland agriculture and expansion of settlements.

This pattern confirms that vegetation-based land-cover classes are the main contributors to carbon storage in the study area. Land-cover classes with higher vegetation density generally store more aboveground biomass carbon than built-up or open land because woody vegetation, mixed crops, and perennial vegetation accumulate carbon in plant biomass (Schimel et al., 2015; FAO, 2014). Conversely, settlement expansion tends to reduce aboveground carbon storage because built-up surfaces contain limited vegetation biomass and have lower carbon-storage capacity (Tao et al., 2015; Zhang et al., 2020).

Although the total carbon stock in 2024 remained higher than that in 2014, the decline after 2019 indicates increasing ecological pressure. This finding suggests that the carbon-storage function of the Gunungpati District is sensitive to the balance between vegetation-based land cover and built-up land expansion. Therefore, maintaining mixed agricultural landscapes, plantations, rice fields, and other vegetated areas is essential to preserve the district's role as a carbon-storage area and green open space reserve.

3.3. Rate of Carbon-Stock Change During 2014–2019, 2019–2024, and 2014–2024

Changes in the carbon stock during the observation period were quantified using the stock difference method. This method estimates the difference in carbon stock between two observation years and divides it by the time interval to obtain the annual rate of change in carbon stock.

Table 6. Matrix of Carbon Reserve Changes in 2014, 2019, and 2024 (tons of C)

2014/2024	Plantation Forest	Plantations	Settlements	Open Land	Water bodies	Dryland Agriculture	Mixed Dryland Agriculture	Rice fields	Total (tons of C)
Plantation Forest	-	23,43	-	-	-	-	-	-	23,43
Plantations	-	658,89	-	-	-	221,02	497,46	-	1.377,36
Settlements	-	-	2.873,63	-	-	-	1.316,76	-	4.190,38
Open Land	-	-	-	-	-	-	-	-	-
Water bodies	-	-	-	-	-	-	-	-	-
Dryland Agriculture	-	-	1.243,08	8,81	-	-	156.050,21	77,53	157.379,63
Mixed Dryland Agriculture	-	159,61	414,74	-	-	4,91	75.076,14	29,93	75.685,32
Rice fields	-	-	99,97	-	-	-	-	1.264,07	1.364,04
Total (tons of C)	**-**	**841,93**	**4.631,41**	**8,81**	**-**	**225,93**	**232.940,56**	**1.371,53**	**240.020,17**

During 2014–2019, total carbon stock increased from 137,404.12 tons C to 268,488.02 tons C, indicating a net increase of 131,083.90 tons C. This corresponds to an average annual increase of approximately 26,216.78 tons C/year. During 2019–2024, total carbon stock decreased from 268,488.02 tons C to 240,020.17 tons C, indicating a net decline of 28,467.85 tons C or approximately 5,693.57 tons C/year. Over the entire 2014–2024 period, carbon stock increased by 102,616.05 tons C, equivalent to an average annual increase of approximately 10,261.61 tons C/year.

The positive change in carbon stock from 2014 to 2019 was primarily associated with the conversion or reclassification of dryland agriculture to mixed dryland agriculture. However, this increase should be interpreted with caution because the estimation was based on land-cover class coefficients rather than direct field biomass measurements. The stock-difference method is appropriate for estimating temporal changes in carbon stocks when consistent land-cover data and carbon-stock coefficients are available; however, its accuracy depends strongly on the reliability of land-cover classification and coefficient assignment (IPCC, 2006; Röhling et al., 2016).

The negative carbon stock change from 2019 to 2024 provides stronger evidence of ecological pressure related to settlement expansion. As shown in the land-cover analysis, settlements increased during this period, whereas mixed dryland agriculture decreased. This transition reduced the estimated carbon-storage capacity of the landscape. Similar patterns have been reported in studies showing that conversion of vegetated land into built-up areas decreases ecosystem carbon storage and weakens land-based climate-mitigation functions (Tagesson et al., 2020Fadhli et al., 2021; Permata & Rahayu, 2021).

Overall, the rate of change in carbon stocks demonstrates that the Gunungpati District still retained a net carbon stock gain over the full 2014–2024 period; however, the declining trend after 2019 indicates that this function may be reduced if settlement expansion continues. These findings confirm that land-cover change and carbon-stock dynamics are closely linked. Therefore, controlling the conversion of vegetation-based land covers into built-up areas is essential to maintain the contribution of the Gunungpati District to urban ecological resilience and climate-change mitigation.

4. CONCLUSIONS

This study demonstrated that land-cover dynamics substantially influence above-ground biomass carbon stocks in the Gunungpati District during 2014–2024. The main landscape transformation was characterized by a sharp decrease in dryland agriculture, the dominance of mixed dryland agriculture, and the continuous expansion of settlements. These changes indicate that the Gunungpati District is undergoing a peri-urban transition in which agricultural and vegetated landscapes are increasingly affected by urban development pressure.

The estimated carbon stock increased from 137,404.12 tons C in 2014 to 268,488.02 tons C in 2019, before declining to 240,020.17 tons C in 2024. The annual change in carbon stock was positive during 2014–2019 but became negative during 2019–2024, reflecting the ecological impact of settlement expansion and the reduction in vegetation-based land cover. Although the district maintained a net carbon stock gain over the full observation period, the post-2019 decline indicates a potential weakening of its carbon-storage function.

These findings confirm that protecting vegetation-based land cover is essential to maintain the ecological role of the Gunungpati district as a green open space reserve and to support climate change mitigation. Future studies should integrate higher-resolution imagery and field-based biomass measurements to reduce uncertainty in land-cover classification and carbon stock estimation.

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