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Spatial and socioeconomic characteristics of CO_2 emissions and sequestration in Indonesian cities

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ABSTRACT

In dealing with the impacts of climate change, mitigation efforts play a crucial role. As one of the G20 countries on the list of the top 5 biggest contributors to emissions, Indonesia must play an active role. With all their characteristics and as one of the most significant contributors to global emissions, cities are fully responsible as a core area for climate mitigation. By analyzing the spatial and socioeconomic characteristics within the city scope, this study examines 32 representative cities and municipalities in Indonesia to understand the condition of carbon emissions and sequestration. Emissions and sequestration in selected cities in Indonesia show varying statuses; most cities have higher emission levels than sequestration, but some cities do the opposite. In addition, emissions and sequestration are also influenced by many complex and interrelated factors, including spatial (distribution, intensity, LULC, geographical conditions, total area), social (total population, urbanization rate, employment rate), economic (GDP/GRDP), and technological (industry structure and energy sector). As an archipelagic country, the uniqueness of cities in Indonesia, primarily located in coastal and waterfront areas, also influences the emission intensity, which tends to be lower in these areas on a micro basis. Cities classified as economically developed contribute more emissions at the national level. Therefore, a characteristic-based classification of the selected cities can encourage policy implications according to the characteristics of each city. These cities can learn from each other, especially from cities with high sequestration rates, to develop in a sustainable way while supporting national mitigation targets.

1. Introduction

Climate change has been a serious issue for the last few decades, and the future will also cause severe impacts on humans and nature with increasing risk trends [1,2]. Mitigating climate change is one of the efforts to overcome it sustainably [3]. Climate change mitigation cannot be separated from efforts to reduce carbon emissions while increasing the ability to absorb carbon in an area [4]. As one of the core areas for mitigating climate change, urban regions' role is dominant in emissions and sequestration. Cities are the most significant contributors to emissions for a country, while other areas around it have the opposite potential as carbon sinks. However, if the role of cities related to carbon absorption capabilities can be increased, then emission levels also have the potential to be reduced. Therefore, it is essential to understand the status of carbon emissions and sequestration in each city within a country so that it can estimate its potential to contribute to country-level climate mitigation.

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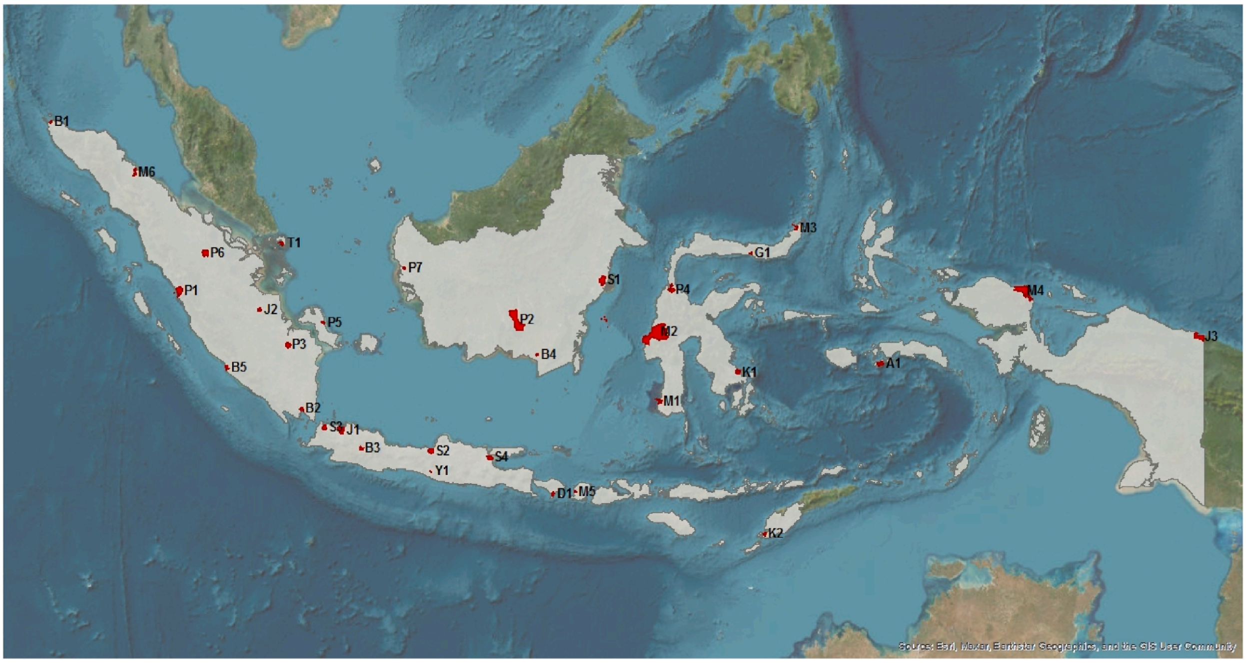
Some factors influence carbon emissions and sequestration. Previous studies have shown that many indicators affect carbon emissions and the area's absorption ability. The factors include spatial and socioeconomic factors, such as spatial adjacency, land use and land cover, landscaping space, total population, gross domestic product (GDP), GDP per capita, energy sector and consumption, energy consumption per GDP and capita, industry structure (primary, secondary, and tertiary), urbanization level, and employment rate [5–13]. Each of these factors can represent the characteristics of the city. Understanding the characteristics of cities related to carbon emissions and sequestration through these factors can identify potential indicators for improving or maintaining their performance. Therefore, analyzing factor-based characteristics in studies of carbon emissions and sequestration at the city level is essential.

Spatial characteristics are crucial in climate change mitigation and carbon-related studies. Several previous studies have combined carbon-related research from a spatial perspective. Hong et al. have conducted a literature study on urban spatial structure and carbon emissions; the output shows that spatial structure has a real effect on carbon emissions, and this spatial approach tends to be more effective in reducing emissions and building low-carbon cities [14,15]. The factors that affect emissions also play a role in forming spatial heterogeneity patterns of carbon emissions [16]. In addition, carbon emissions also flow from one place to another in a spatial dimension and have the potential to form a network [17]. Wang et al. in their study, confirmed that a spatial perspective could describe the structure and distribution of carbon emissions in an urban area and support carbon neutrality targets [18]. The spatial dimension of carbon emissions can also be connected to land use and land cover, including using remote sensing data or other big data sources [19]. Spatial characteristics can help stakeholders manage carbon emissions using location-based methods while increasing the potential for carbon absorption at the micro-to medium-scale.

Indonesia is one of the top 5 biggest contributors to emissions in G20 countries [4]. Based on the emission gap report from UNEP in 2022, most of the G20 members are still far from the nationally determined contribution (NDC) targets and the 2030 mitigation commitment. Indonesia is one of the countries that carried out post-COP 26 NDC updates. G20 support for Indonesia in achieving the NDC targets is through investment and funding in various sectors (such as energy transition), openness to up-to-date information on developments and policies implemented globally and in developed countries, and cooperation with G20 members. However, compared to other G20 members, such as Australia, Canada, the EU, Republic of Korea, the UK, and the USA, Indonesia's emissions reduction trend until 2030 is still relatively slow, with the 2060 net-zero target that tends to be longer [4]. Therefore, Indonesia needs to set more ambitious NDC targets and policies to equalize its position with other countries in the G20. The action and implementation of targets and policies also need further improvement in various sectors and levels. Cities are crucial in pushing Indonesia to align with G20 countries regarding climate targets and policies.

Few studies discuss carbon emissions and sequestration at the city level in Indonesia. In general, previous studies discussed carbon emissions and sequestration only from specific sectors or objects, for example, tropical forests, mangroves, protected areas, oil palm plantations, environmental management, energy consumption, and so on [20–25]. In addition, studies at the city level tend to only choose one city as the study area [26–28]. This study's novelty is the selection of many cities as samples to provide a representative picture of carbon emissions and sequestration in Indonesia, along with their characteristics. By combining the analysis of the spatial and socioeconomic characteristics of carbon emissions and sequestration in Indonesian cities, the aims of this study are as follows: 1) to



Source: Esri, Maxar, Earthstar Geographics, and the GIS User Community

Fig. 1. Location of selected cities.

understand the status of carbon emissions and sequestration in cities and municipalities in Indonesia; 2) to reveal the spatial and socioeconomic characteristics related to emissions and sequestration in Indonesian cities; and 3) to classify the cities based on their characteristics and identify their potential contributions to climate change mitigation efforts at the national level.

This paper has several sections. The first section discusses this study's background and research purposes. The second section is materials and methods, including study areas, data sources, methods, and research frameworks. The results of all analyses in this study are in the third section. The final sections are discussion and conclusion, which discuss the study's implications, limitations, and main outcomes.

2. Material and methods

2.1. Case study area

The case study areas in this research cover cities and municipalities in Indonesia that were chosen based on data availability. After the screening process, 32 cities were selected. The city code was given for each selected city and municipality to simplify each city's name for the following processes. The list of selected cities and municipalities is shown in Supplementary Material Table S1. Most of the major cities in Indonesia and the locations for each selected city in this study are in the coastal and waterfront areas, while a few are in the inland region (Fig. 1).

2.2. Data source

This study uses various types of data from many sources, such as CO_2 emission data, spatial data, socioeconomic data, and data from other additional sources. The data sources used in this study include a) The Open-Data Inventory for Anthropogenic Carbon Dioxide (ODIAC) for 2019 CO_2 emissions https://db.cger.nies.go.jp/dataset/ODIAC/ [29]; b) socioeconomic data from the Central Bureau of Statistics of each selected city/municipality in 2020 (report that provide 2019 actual data); c) Gross Regional Domestic Product of Regencies/Municipalities in Indonesia 2017–2021 (BPS-Statistics Indonesia); d) Gross Regional Domestic Product by Industry 2017–2021 for each selected city/municipality; e) Provincial Statistics Report 2020 (report that provide 2019 actual data); f) Boundary maps of all selected cities from Indonesian Geospatial Information Agency and Ministry of Home Affairs – Directorate General of Population and Civil Registration; g) Land cover data of all selected cities from Ministry of Environment and Forestry Republic of Indonesia; and h) relevant available data from published international peer-reviewed journals or official websites. Detailed information about data sources and descriptions can be seen in Supplementary Material Table S2.

2.3. Estimation of city CO_2 emissions

Carbon emissions were estimated by energy consumption in each sector within the city scope. This study's scope of carbon emissions adopts the terms from the IPCC and WRI/WBCSD accounting scopes. The scope of this study is Scope 1, which covers carbon emissions that occur within the city boundary, such as carbon emissions from electricity, household, transportation, commercial, industry, and other sectors within the city boundary.

The equation for total carbon emissions is as follows (Eq. (1)):

$$\mathrm{CE} = \sum_{i}^{j} \mathrm{EijxFij} \tag{1}$$

where CE = total carbon emissions (ton C), Eij = energy consumption of fuel j by sector i, and Fij = carbon emission factor by fuel j in sector's energy consumption i.

Emissions grid map data from the ODIAC was visualized using ArcMap 10.8. CO_2 emissions from the ODIAC are shown in 1 km × 1 km grid maps that can be applied to city-scale emissions estimation, especially from a spatial perspective. Based on the grid map from the ODIAC, the total carbon emissions in selected cities were calculated. Calculating total carbon emissions is done by adding up all the grid values on the grid map in each selected city, and the process uses ArcMap 10.8 software.

2.4. Carbon sequestration calculation based on land cover

The land cover classification in Indonesia consists of twenty-three groups. However, referring to the IPCC guidelines, which contain classifications of land cover classes, Indonesia's land cover can be classified into seven major groups: forest, cropland, grassland, wetland, settlement, other lands, and no data. As published by the Ministry of Environment and Forestry Republic of Indonesia in 2016 [30], land cover classification in Indonesia and the IPCC are shown in Supplementary Material Table S3.

The calculation of carbon sequestration for different land cover types uses coefficients from previous studies [31]. The coefficient for each land cover type is widely accepted and used in carbon sequestration research. The calculation is as follows (Eq. (2)):

$$\mathrm{CS_q} = \mathrm{k_q} \mathrm{S}_q \tag{2}$$

where $\mathrm{CS_q}$ represents the carbon sequestration of land cover type q (kg C), $\mathrm{k_q}$ is the carbon sequestration coefficient (kg C/m^2. yr), and

S_q (m^2) represents the total area of land cover q. The visualization of spatial maps of carbon sequestration in selected cities was done using ArcMap 10.8 software.

2.5. Carbon balance index (CBI)

The carbon emissions and carbon sequestration ratio is the carbon balance index (CBI). The equation is as follows (Eq. (3)):

$$\mathrm{CBI} = \frac{CE}{CS} \tag{3}$$

where CBI = carbon balance index, CE = carbon emissions (ton C), and CS = carbon sequestration (ton C). The CBI value equals 1, showing the balance between carbon emissions and carbon sequestration. If the CBI value > 1, then the level of carbon emissions is greater than carbon sequestration; if the CBI value < 1, then carbon emissions are lower than carbon sequestration. CBI value < 1 is a good condition for achieving low carbon targets.

2.6. CO_2 emissions influencing factors

Carbon emissions are influenced by several factors, including total area, total population, GDP per capita, urbanization rate, employment rate, industry output value over GDP (primary, secondary, and tertiary), total energy consumption, and energy consumption per GDP. Detailed information on this study's carbon emissions driving forces can be found in Supplementary Material Table S4. Carbon emissions driving forces in each city can be used as variables in correlation analysis to determine the influence of each driving force on carbon emissions at the city level in Indonesia. SPSS software was used to conduct correlation analysis and obtain a regression model of carbon emissions and the driving forces in selected Indonesian cities.

2.7. Research framework

The framework of this research is shown in Fig. 2.

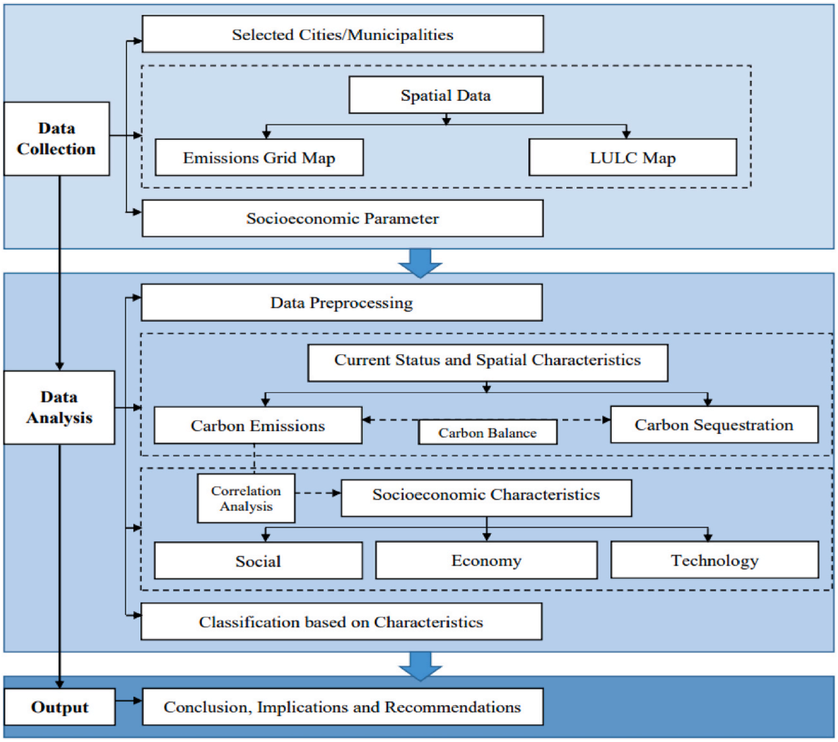


Fig. 2. Research framework.

3. Result

3.1. Carbon emissions, sequestration, and balance status in selected cities

The results of estimating carbon emissions in selected cities in Indonesia show varying levels of emissions (Fig. 3). Cities with the highest emission levels include J1 (Jakarta, 10,386.001 ktCO$_2$), S4 (Surabaya, 3423.985 ktCO$_2$), M6 (Medan, 2172.610 ktCO$_2$), P6 (Pekanbaru, 1474.095 ktCO$_2$), and B3 (Bandung, 1113.827 ktCO$_2$). These cities are classified as major cities in Indonesia. Jakarta is Indonesia's capital, center of government and economy. Jakarta is also the most populous city with the highest population, so the emissions produced by this city are ranked first. The city with the second highest emission level is Surabaya, the second largest city in Indonesia and is the core of the economy in the central part of the country. Medan and Pekanbaru have good levels of economy and development in the western Indonesian region, especially the island of Sumatra, which has important hubs such as international airports and seaports. Bandung is the third-largest city in Indonesia, located in the highlands but relatively close to Indonesia's capital, Jakarta.

Fig. 3 also shows cities that have lower emission levels. The five cities with the lowest emission levels include M2 (Mamuju, 17.118 ktCO$_2$), M4 (Manokwari, 54.536 ktCO$_2$), G1 (Gorontalo, 71.678 ktCO$_2$), K2 (Kupang, 94.261 ktCO$_2$), and A1 (Ambon, 101.507 ktCO$_2$). These cities are all located in Indonesia's eastern region. These cities' general condition still has a large green area and a lower population, especially Mamuju and Manokwari. In addition, low emission levels are also possible due to the high level of carbon absorption in these cities.

Carbon sequestration can show the ability of a region to absorb carbon emissions. In this context, the level of carbon absorption considers the types of land cover. Based on an analysis of selected cities, five cities have the highest levels of carbon sequestration, namely: M2 (Mamuju, 205.368 ktCO$_2$), M4 (Manokwari, 95.596 ktCO$_2$), P2 (Palangka Raya, 79.207 ktCO$_2$), B1 (Banda Aceh, 78.574 ktCO$_2$), and J3 (Jayapura, 33.477 ktCO$_2$) (Fig. 4). Interestingly, Mamuju and Manokwari, which previously had the lowest carbon emission levels, had the highest carbon sequestration levels. Five cities with the lowest level of carbon sequestration include Y1 (Yogyakarta, 0.000076 ktCO$_2$), M5 (Mataram, 0.015 ktCO$_2$), B3 (Bandung, 0.019 ktCO$_2$), B4 (Banjarmasin, 0.028 ktCO$_2$), and K2 (Kupang, 0.032 ktCO$_2$). A high level of carbon sequestration is an ideal condition to support climate change mitigation. In contrast, areas with a low level of carbon sequestration need to increase their carbon absorption capabilities.

The carbon balance index analyzes carbon emissions and sequestration results in its calculations. Carbon emissions are calculated from the extraction of values on the emission grid map, while carbon sequestration is obtained based on the land cover type (Table 1). Based on the carbon balance index with a reference value of 1, selected cities can be grouped into three groups. The first group has CBI value below 1, including M2 (Mamuju, 0.083) and M4 (Manokwari, 0.570). The first group is excellent because the value of carbon emissions is lower than sequestration. The second group is the cities with CBI scores above 1 but below 2, namely B1 (Banda Aceh, 1.996) and P2 (Palangka Raya, 1.906). The two cities in this group have higher emission levels than carbon sequestration, but the

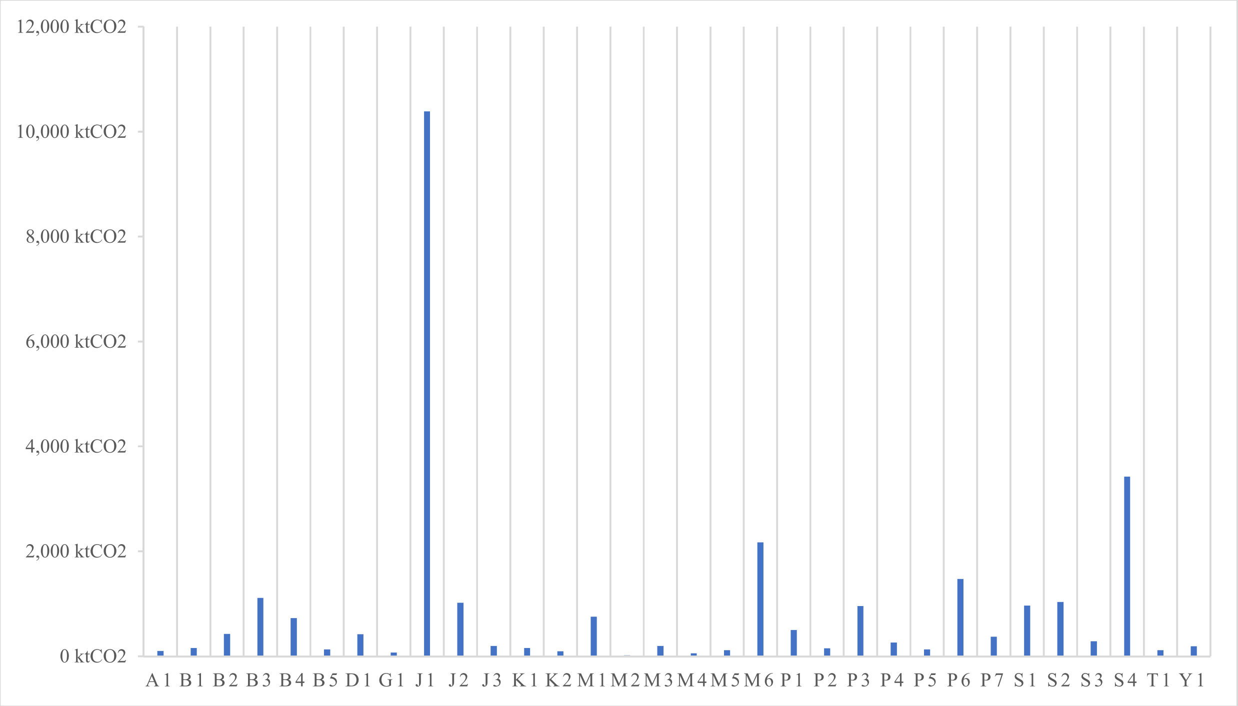


Fig. 3. CO$_2$ emissions of selected cities.

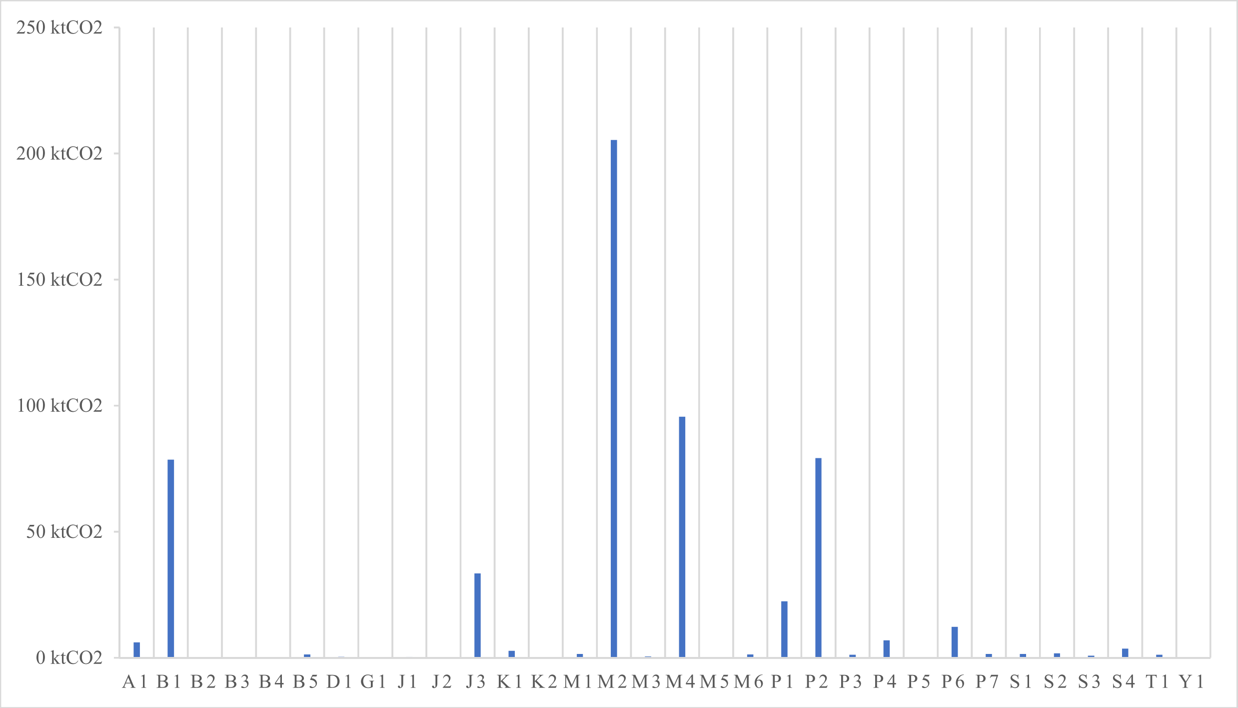


Fig. 4. CO_2 sequestration of selected cities.

carbon absorption performance can almost offset the emission levels. The third group is cities with a high CBI score, indicating high emissions that carbon sequestration cannot adequately offset. The third group consists of all cities not mentioned in the first and second groups. This third group urgently requires an effective solution to reduce emission levels and increase sequestration.

3.2. Spatial characteristics of CO_2 emissions and sequestration in Indonesian cities

3.2.1. Area of selected cities

The area size is one of the parameters in carbon emission and sequestration research. The comparison chart of each selected city's area (in km^2) is shown in Supplementary Material Fig. S1. Cities with the most significant area are M2 (4954.57 km^2), M4 (3168.28 km^2), P2 (2853.12 km^2), J3 (940 km^2), and S1 (718 km^2). At the same time, cities that have the smallest area include Y1 (32.5 km^2), M5 (61.3 km^2), B1 (61.36 km^2), G1 (79.59 km^2), and B4 (98.46 km^2). The area of each city area cannot fully show the extent of urban development but only describes administrative boundaries. Therefore, in several cities with large areas, the area is not 100 % built, but instead in the form of green or natural areas.

3.2.2. Spatial characteristics of CO_2 emissions and sequestration in selected cities

A map of the distribution of CO_2 emissions in selected cities in Indonesia can spatially show the intensity of carbon emissions on a macroscale using a grid map (Figs. 5–8). The map is depicted at varying scales to show the condition of each city with its respective city code. The range of colors indicates the intensity of carbon emissions. The green color shows the lowest emission, while the red color shows the highest emission.

Figs. 5–8 show that each selected city has an uneven emission intensity distribution. The classification of cities based on emission intensity distribution includes the moderate-to-high group, the moderate group, and the medium-to-low group. Several cities have moderate to high dominant emission intensities, including B1, B2, B3, B4, D1, J1, J2, M1, M5, M6, P7, S2, S4, and Y1. Although some cities have high emission intensity, they also have relatively low emission points, including cities B1, B4, D1, J2, M1, M6, S2, and S4. The points with low emission levels tend to be related to the function or condition of the area. Each point function or condition in each city is B1 (areas that function as aquaculture), B4 (areas bordering large rivers), D1 (areas bordering the coast and sea), J2 (areas bordering intersect with major rivers), M1 (small island area in the middle of the ocean), M6 (coastal/seaside location), S2 (the coastal area that functions as aquaculture), and S4 (the seaside site that functions as aquaculture). The points with the lowest emissions in these cities have something in common, which is related to water areas such as rivers, seas, coasts, and aquaculture. Meanwhile, each city's area that is the center of emission intensity originates from downtown and spreads to surrounding areas.

Cities with medium dominant emission intensities, namely: P3, P5, P6, S1, S3, and T1. This second group is a group that has moderate emission intensity in the city area, so almost the entire area is yellow. Meanwhile, cities with moderate to low emission intensity are A1, B5, G1, J3, K1, K2, M2, M3, M4, P1, P2, and P4. Cities with emission intensity in this third group tend to have only

Table 1
CO_2 emissions, sequestration, and balance index of selected cities.

City	CE ($ktCO_2$)	CS ($ktCO_2$) based on land cover type				Σ CS ($ktCO_2$)	Carbon Balance Index (CBI)
		Forest	Cultivated Land	Grassland	Wetland		
A1	101.507	5.676	0.064	0.351	0	6.092	16.664
B1	156.824	0	78.175	0.002	0.397	78.574	1.996
B2	426.253	0	0.042	0.003	0.013	0.059	7231.854
B3	1113.827	0.004	0.015	0	0	0.019	58245.394
B4	729.665	0	0.028	0	0	0.028	26203.576
B5	130.751	1.117	0.044	0.062	0.117	1.341	97.537
D1	420.063	0.380	0.014	0.014	0.017	0.426	986.617
G1	71.678	0	0.015	0.079	0	0.093	769.876
J1	10,386.001	0.066	0.026	0	0.268	0.359	28893.666
J2	1020.751	0	0	0.201	0	0.201	5087.450
J3	194.399	33.064	0.090	0.317	0.006	33.477	5.807
K1	159.416	1.954	0.063	0.415	0.341	2.772	57.505
K2	94.261	0	0.020	0	0.011	0.032	2967.909
M1	754.450	0.154	0.020	0.008	1.322	1.505	501.422
M2	17.118	196.691	0.686	5.548	2.443	205.368	0.083
M3	194.536	0.397	0.068	0.029	0.012	0.506	384.543
M4	54.536	93.973	0.124	1.499	0	95.596	0.570
M5	117.958	0	0.015	0	0	0.015	8002.061
M6	2172.610	0.453	0.020	0.092	0.798	1.363	1594.332
P1	503.018	21.956	0.134	0.327	0	22.417	22.439
P2	150.973	75.408	0.255	3.543	0	79.207	1.906
P3	957.560	0.924	0.050	0.224	0	1.197	799.788
P4	263.156	6.018	0.046	0.809	0.009	6.882	38.237
P5	129.851	0.070	0.032	0.068	0.060	0.231	562.328
P6	1474.095	11.815	0.067	0.023	0.393	12.297	119.871
P7	373.426	1.547	0.008	0	0	1.554	240.255
S1	963.803	0.209	0.109	1.209	0	1.526	631.394
S2	1035.830	0.315	0.106	0	1.337	1.759	588.923
S3	284.903	0.161	0.142	0	0.532	0.835	341.166
S4	3423.985	0.040	0.034	0	3.578	3.652	937.549
T1	117.155	1.141	0.026	0.076	0.011	1.254	93.435
Y1	189.437	0	0.000076	0	0	0.000076	2492593.145

Note: Calculation and analysis results.

emission intensity centers in the downtown area. Several reasons influence the dominance of low emission intensity in these cities, namely: 1) the administrative area of cities is large but still dominated by green or forest areas; 2) the built-up area in the city is smaller; 3) the city area has a direct border with the sea area or the surrounding area that has not been built up; and 4) reasons for the development and economic progress in urban areas. But even so, the lower emission intensity has the potential to contribute more to the achievement of the national climate mitigation target.

The spatial perspective of carbon sequestration in cities in Indonesia is obtained based on the type of LULC. The sequestration potential map refers to each city's land cover map (Figs. 5–8). The LULC classification refers to the Ministry of Environment and Forestry Republic of Indonesia, while coefficient-based calculations refer to the IPCC classification. Based on IPCC classification, in the Indonesian context, LULC types that have carbon sequestration potential include forest, cultivated land, grassland, and wetland. The color of the sequestration map in each city shows the total amount of carbon absorbed in the area. The red color shows low or even zero carbon sequestration, while the green color shows the presence of carbon sequestration in the area at different levels based on the LULC type.

In Figs. 5–8, the cities with dominant LULC types not included in the carbon sequestration calculation are B1, B2, B3, B4, D1, J1, J2, K2, M1, M5, M6, P7, S2, S4, and Y1. These cities have dominant residential areas that make up more than 50 % of the total urban area. It shows that these cities can be classified as big cities with a high population, larger residential areas, and built spaces. Cities not mentioned in this group tend to have various types of LULC. This condition also shows a relationship between the area's natural characteristics and land use. Most cities located in lowland areas tend to use their land for agricultural and peat conservation areas, while coastal regions tend to have aquaculture areas and mangrove forests. In addition, several cities have plantation and mining areas within their city administrative regions.

Several cities are still dominant with areas included in the carbon sequestration calculation, such as A1, J3, K1, M2, M4, P1, P2, P4, and S3. These cities have varied LULC and still have more expansive forests, cultivated land, grassland, and wetlands than the residential areas. Therefore, these cities have higher sequestration potential. Suppose the spatial map of emission intensity and sequestration is juxtaposed. In that case, the relationship between LULC types, the level of emissions produced, and the amount of carbon absorbed can be seen clearly. Therefore, spatial-based climate mitigation solutions at the city scale can be more targeted with emissions maps and sequestration potential from the land cover map. Cities with higher carbon sink potential areas can continue to maintain the status, while cities with lower carbon sink areas can increase the sequestration areas.

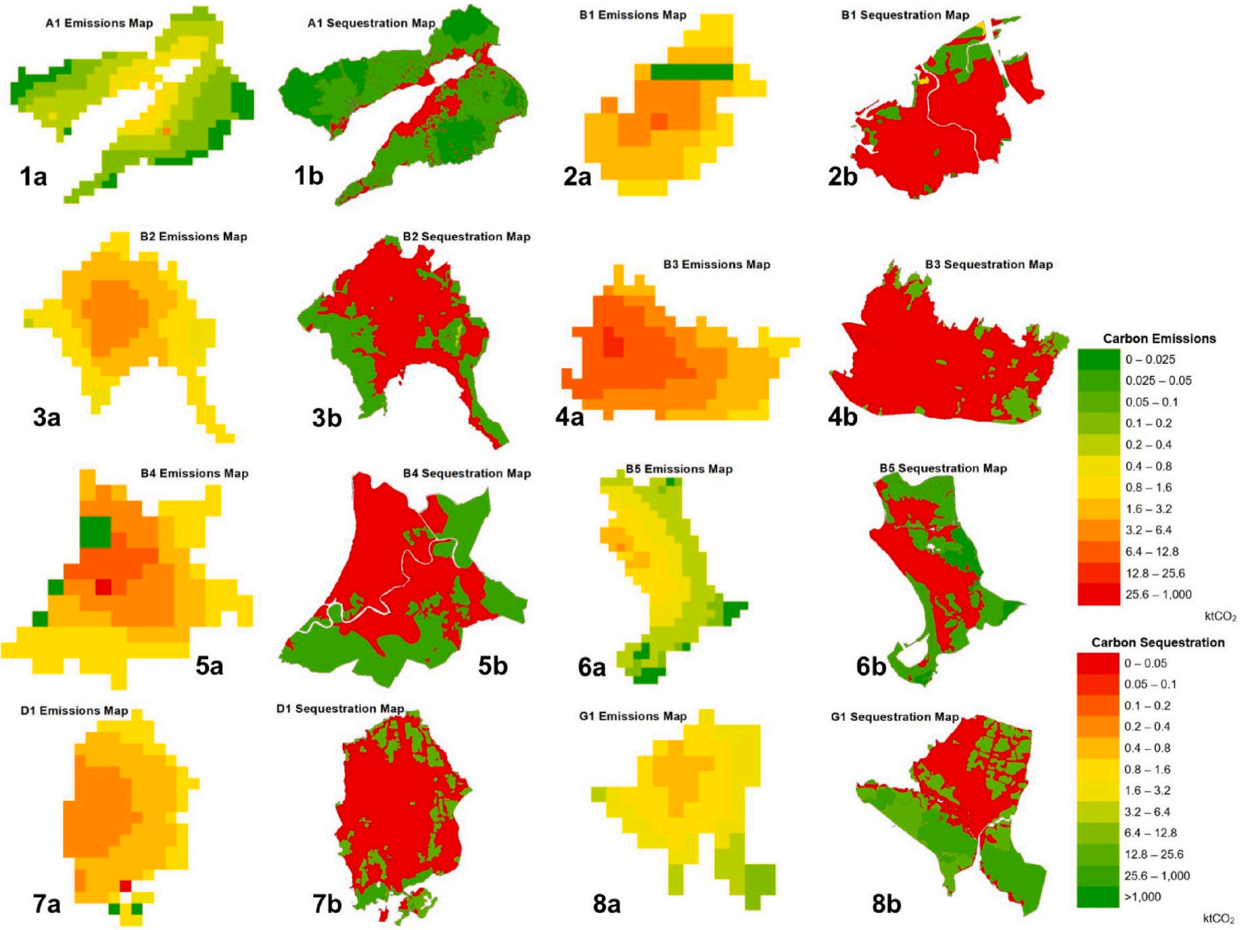


Fig. 5. 1a-1b: Spatial distribution of emissions and sequestration of A1. 2a-2b: Spatial distribution of emissions and sequestration of B1. 3a-3b: Spatial distribution of emissions and sequestration of B2. 4a-4b: Spatial distribution of emissions and sequestration of B3. 5a-5b: Spatial distribution of emissions and sequestration of B4. 6a-6b: Spatial distribution of emissions and sequestration of B5. 7a-7b: Spatial distribution of emissions and sequestration of D1. 8a-8b: Spatial distribution of emissions and sequestration of G1.

3.3. Socioeconomic characteristics of CO_2 emissions in Indonesian cities

3.3.1. Social parameter status

Parameters included in social parameters in terms of emissions include population, urbanization rate, and employment rate. The graphs of selected cities' total population, urbanization rate, and employment rate can be found in Supplementary Material Figs. S2–S3. These parameters are closely related to carbon emissions in urban areas because the parameters intersect with the city's inhabitants. From the population level, cities that are included in high-population cities in Indonesia are J1 (10, 535, 515 persons), S4 (3,158,943 persons), B3 (2,507,888 persons), M6 (2,279,894 persons), and S2 (1,814,110 persons). Cities with the lowest population, among others: M4 (188,932 persons), G1 (200,558 persons), P5 (215,379 persons), T1 (220,812 persons), and P2 (266,000 persons). The highest-population cities are mostly included in the list of the highest-emissions cities, such as J1, S4, M6, and B3. Meanwhile, the cities with the lowest population are included in the list of the lowest emission levels, such as M4 and G1.

The level of urbanization can show the percentage of immigrants in an urban area and affect the city's population and emission levels. The urbanization rate is calculated by comparing the city's population with the province's total population. Cities with a high urbanization rate include J1 (99.77 %), D1 (22.461 %), M2 (22.028 %), S1 (21.325 %), and A1 (21.307 %). In comparison, those with a low urbanization rate include B1 (5.032 %), S3 (5.045 %), B3 (5.085 %), S2 (5.225 %), and K2 (8.492 %). The effect of urbanization on emissions can be seen in J1, which has a high number of emissions and a high urbanization rate. J1 is the largest city in Indonesia, consisting of five administrative areas in one province, which can provide many job opportunities for migrants from outside the region.

On the other hand, although A1 has a relatively high urbanization rate, it actually has a lower emission level. K2, a city with a low urbanization rate, also tends to have a low emission level. Interestingly, B3, which has a low urbanization rate, is one of Indonesia's cities with the highest emission levels. Therefore, although the urbanization rate affects the emission level, the effect can be linear or opposite due to many factors. Cities with high urbanization rates are likely to have lower carbon emissions if the development level and

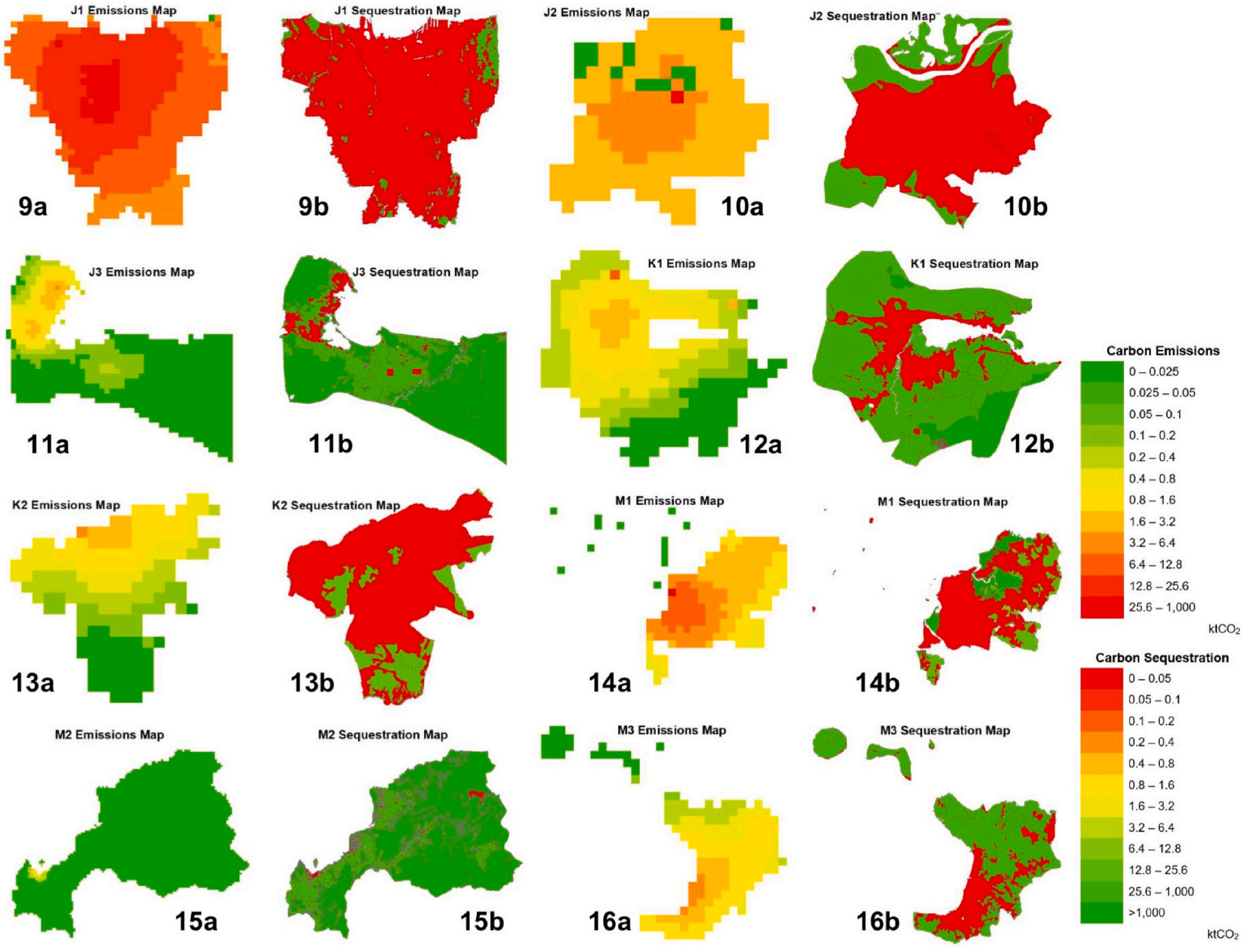


Fig. 6. 9a-9b: Spatial distribution of emissions and sequestration of J1. 10a-10b: Spatial distribution of emissions and sequestration of J2. 11a-11b: Spatial distribution of emissions and sequestration of J3. 12a-12b: Spatial distribution of emissions and sequestration of K1. 13a-13b: Spatial distribution of emissions and sequestration of K2. 14a-14b: Spatial distribution of emissions and sequestration of M1. 15a-15b: Spatial distribution of emissions and sequestration of M2. 16a-16b: Spatial distribution of emissions and sequestration of M3.

economy are not too high, accompanied by maintained natural areas, as in A1. Conversely, cities with low urbanization rates are likely to have higher emissions due to the high level of development and economy along with environmental degradation, as in B3.

The employment rate shows the number of labor resources employed, calculating the ratio of the working population to the working age group. Cities that have a high employment rate include D1 (97,783 %), M2 (97,337 %), B5 (95,715 %), S2 (95,458 %), and Y1 (95,199 %). Cities with low employment rates are J3 (87.630 %), M3 (89.542 %), M1 (89.609 %), K2 (90.221 %), and P7 (90.868 %). K2 is a city with a low employment rate but, at the same time, the lowest emission level. Meanwhile, other cities with high or low employment rates are not included in the list of the lowest or highest emission levels. However, the employment rate still has a significant influence, both directly and indirectly, on the level of emissions. This ratio is influenced by the availability of jobs in urban areas and will also correlate with people's welfare.

3.3.2. Economy parameter status

Economic parameters are the dominant parameters in the development progress of a city, including the emissions level produced in the city. GDP/GRDP per capita can be a representation of economic parameters. The graph of selected cities' GDP/GRDP level is shown in Supplementary Material Fig. S4. Based on the level of annual per capita income, selected cities that have the highest GDP/GRDP include: J1 (268.062 million IDR), S4 (183.761 million IDR), P6 (124.442 million IDR), M1 (116.875 million IDR), and B3 (115.021 million IDR). J1, S4, P6, and B3 can show a close correlation between GDP/GRDP per capita and emission levels because these cities have the highest emission levels in Indonesia. This condition can indicate that the higher the level of the annual income and expense, the emissions produced also tend to be more significant.

For selected cities with the lowest GDP/GRDP, namely: A1 (38.552 million IDR), M2 (38.554 million IDR), M5 (40.017 million IDR), G1 (42.147 million IDR), and B4 (46.589 million IDR). A1, M2, and G1 represent a linear relationship between low per capita

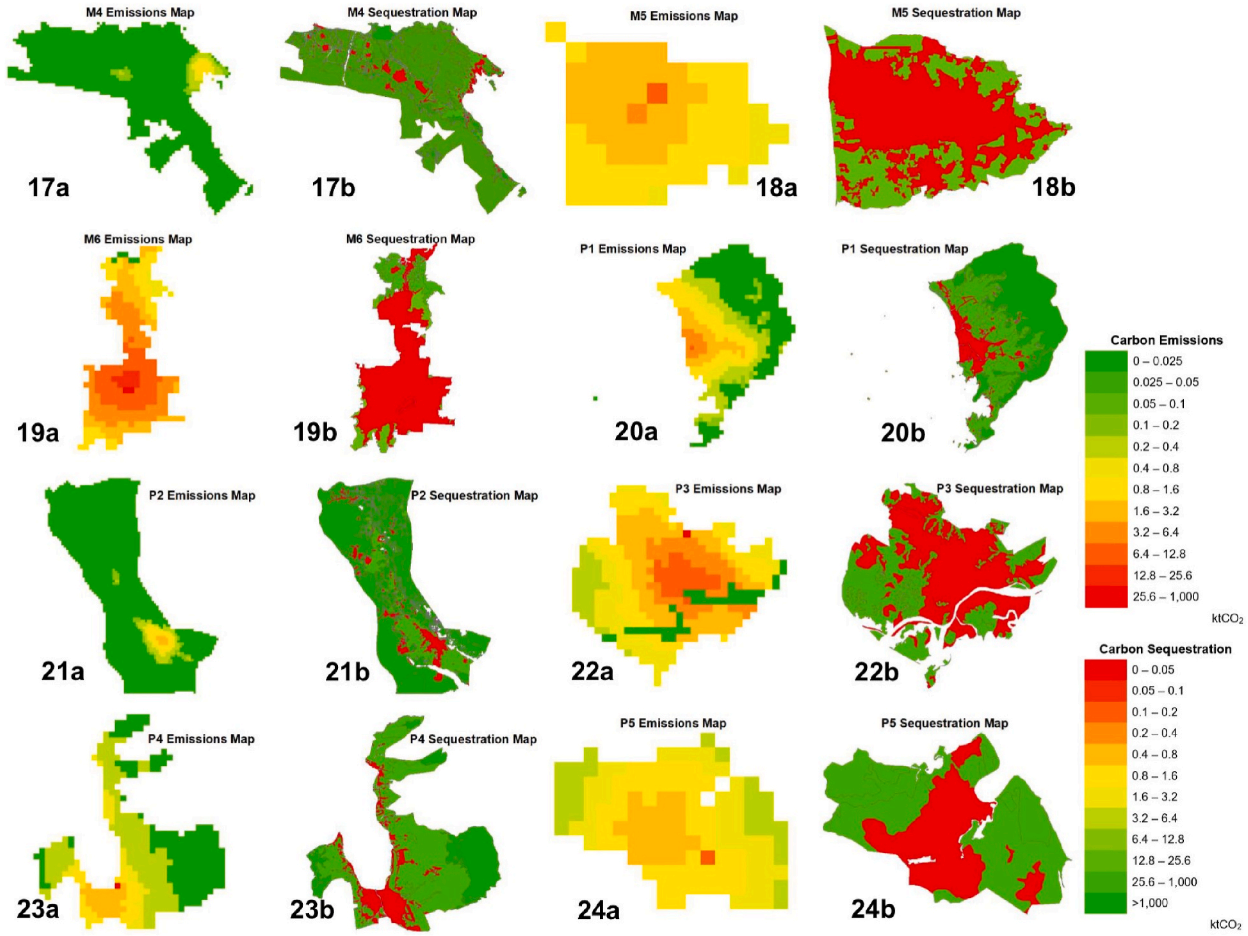


Fig. 7. 17a-17b: Spatial distribution of emissions and sequestration of M4. 18a-18b: Spatial distribution of emissions and sequestration of M5. 19a-19b: Spatial distribution of emissions and sequestration of M6. 20a-20b: Spatial distribution of emissions and sequestration of P1. 21a-21b: Spatial distribution of emissions and sequestration of P2. 22a-22b: Spatial distribution of emissions and sequestration of P3. 23a-23b: Spatial distribution of emissions and sequestration of P4. 24a-24b: Spatial distribution of emissions and sequestration of P5.

income and lower emission levels. These cities show that cities with lower annual per capita income produce lower emissions due to their limited ability to consume energy as well as their limited use of other items that have the potential to generate emissions. However, other emission-triggering factors also cannot be ignored in this context.

3.3.3. Technology parameter status

The technology parameter is a core indicator closely related to technology use, energy, and emissions. Therefore, this parameter can be classified into two important sectors: industry and energy consumption. The industrial sector is divided into primary, secondary, and tertiary industries. Meanwhile, energy consumption is divided into total energy consumption and energy consumption to GDP/GRDP. Due to the limited data available at the city level, energy consumption is limited to electricity.

Most selected cities have a lower percentage of primary industries than secondary and tertiary industries. Cities with the highest primary industry ratio are M2 (39.26 %), M4 (15.87 %), K1 (14.67 %), S1 (14.46 %), and P4 (11.12 %). At the same time, S2 (54.34 %), P6 (49.3 %), P3 (49.27 %), T1 (35.12 %), and M6 (33.6 %) have the highest secondary industry ratio. The highest tertiary industry ratio is occupied by B1 (90.66 %), A1 (86.36 %), M3 (85.44 %), B5 (84.4 %), and Y1 (78.84 %). M6 and P6 are included in the cities with the highest emissions in Indonesia and the highest secondary industry ratio. As an industry that processes raw materials into products or commodities, the secondary industry influences emission levels in the two cities. In contrast, M2 and M4, which have the highest primary industry ratios, have the lowest emission levels, while A1 has low emission levels but a high tertiary industry ratio. The percentage of industry sectors (primary, secondary, and tertiary) in all the selected cities can be found in Supplementary Material Fig. S5.

In the energy sector, total energy consumption and its ratio to GDP are essential to the city's system and emission level. The graphs of each city's total energy consumption and energy consumption per GDP are shown in Supplementary Material Figs. S6–S7. Cities that consume the most energy from electricity include J1 (4,189,654.60 tons of standard coal), S4 (1,096,225.65 tons of standard coal), P6

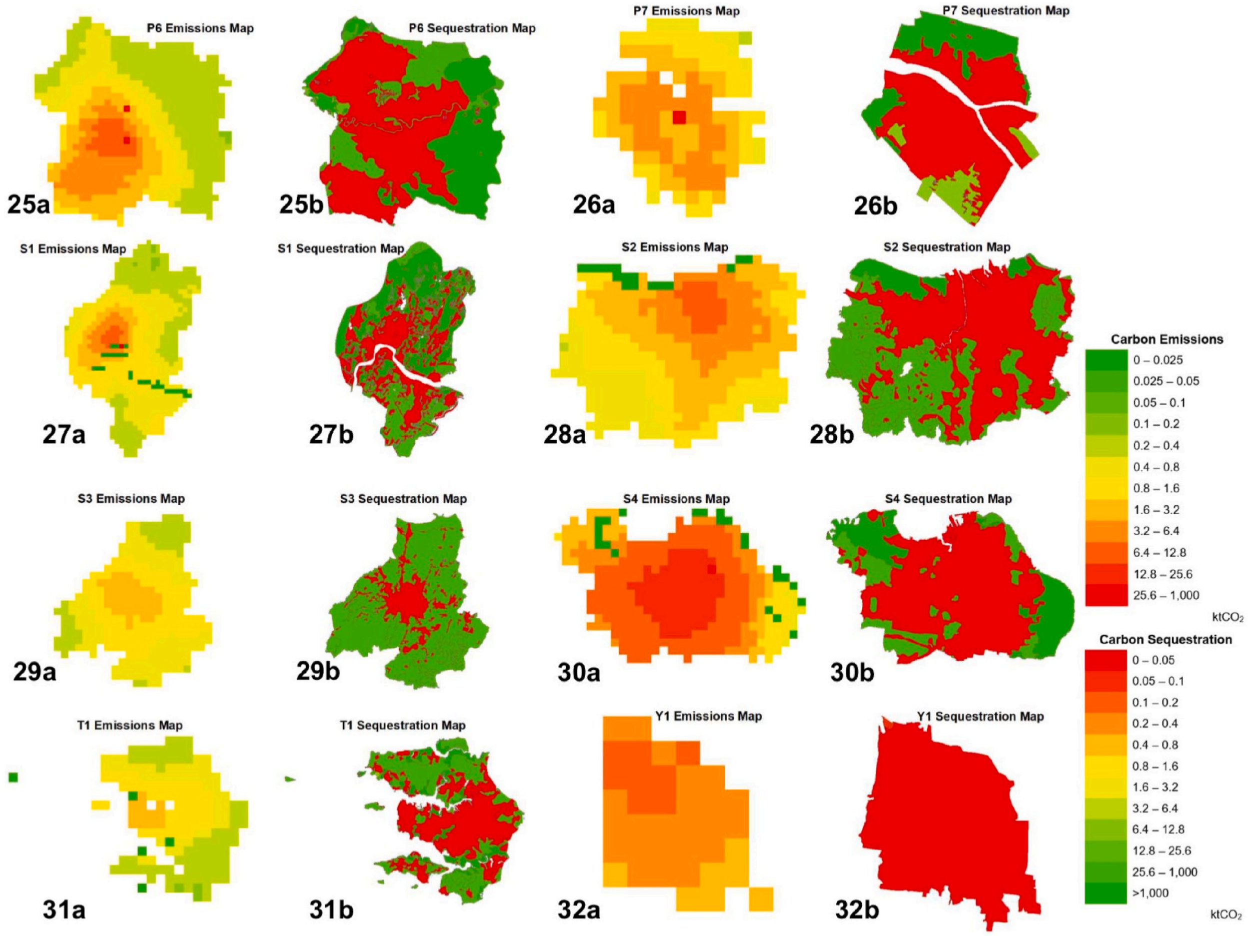


Fig. 8. 25a-25b: Spatial Distribution of Emissions and Sequestration of P6. 26a-26b: Spatial Distribution of Emissions and Sequestration of p7. 27a-27b: Spatial Distribution of Emissions and Sequestration of s1. 28a-28b: Spatial Distribution of Emissions and Sequestration of s2. 29a-29b: Spatial Distribution of Emissions and Sequestration of s3. 30a-30b: Spatial Distribution of Emissions and Sequestration of s4. 31a-32b: Spatial Distribution of Emissions and Sequestration of T1. 32a-32b: Spatial Distribution of Emissions and Sequestration of Y1.

(225,726.98 tons of standard coal), D1 (188,029.96 tons of standard coal), and M3 (180,182.96 tons of standard coal). Cities that have the lowest total energy consumption, namely M1 (117,566 tons of standard coal), M6 (511,198 tons of standard coal), B3 (525,341 tons of standard coal), S2 (563,401 tons of standard coal), and T1 (3098.59 tons of standard coal). The cities with the highest electricity consumption levels and emissions are J1, S4, and P6. The comparison of energy consumption to GDP/GRDP at the lowest levels is occupied by M1, B3, M6, S2, and J3. Meanwhile, on the contrary, M5, J2, M3, B1, and G1 have the highest energy consumption ratio to GDP/GRDP. The energy sector, which is only limited to electricity consumption, can represent a portion of the energy consumed by people in urban areas.

3.4. *Correlation analysis of CO_2 emissions and driving forces*

Correlation analysis involves carbon emissions as the dependent variable and ten driving forces as the independent variable. The results of the analysis using SPSS software show the Sig. F change value is 0.000, meaning the independent and dependent variables are correlated (Sig. F change value < 0.05). Meanwhile, the values of $R = 0.991$ and R square $= 0.981$ show that 98.1 % of carbon emissions at the city level in Indonesia can be explained by the variables involved, while 1.9 % are influenced by other factors outside the model. The statistical analysis results can be seen in Supplementary Material Tables S5–S8. The Pearson correlation matrix from the analysis is shown in Supplementary Material Fig. S8.

The regression model obtained from the statistical analysis for the influence of driving forces on carbon emissions at the city level in Indonesia with a sample of 32 cities is as follows (Eq. (4)):

$$Y = -128.429 + 0.001\ X2 + 4.592\ X3 + 3.269\ X4 - 5.154\ X5 + 2.905\ X6 + 7.111\ X7 + 0.001\ X9 + 275.728\ X10 \tag{4}$$

where Y = CE; constant = value on the coefficient table; X1 = TA; X2 = TP; X3 = GP; X4 = UR; X5 = ER; X6 = PG; X7 = SG; X8 = TG;

X9 = TC; X10 = EG. X1 has a coefficient value of 0, and X8 is an excluded variable with the minimum influence on the dependent variable, so it is removed from the equation. The regression model (Eq. 4) shows the influence of each involved independent variable on changes in carbon emissions at the city level in Indonesia generally. The interpretation based on Eq. 4 is as follows:

a. Intercept: If there is no influence of any independent variable on CE, then the CE value will decrease according to the constant −128,429 or reduce by 128,429 ktCO2.
b. Variable X1 = TA: Changes to TA will not affect the value of CE.
c. Variable X2 = TP: 1 person increase in TP leads to an increase of CE by 0.001 ktCO2
d. Variable X3 = GP: 1 million IDR increase of GP, lead to an increase of CE by 4.592 ktCO2
e. Variable X4 = UR: 1 % increase of UR leads to an increase of CE by 3.269 ktCO2
f. Variable X5 = ER: 1 % increase of ER leads to a decrease of CE by 5.154 ktCO2
g. Variable X6 = PG: 1 % increase of PG leads to an increase of CE by 2.905 ktCO2
h. Variable X7 = SG: 1 % increase of SG leads to an increase of CE by 7.111 ktCO2
i. Variable X8 = TG: Changes to TG will not affect the CE value
j. Variable X9 = TC: 1 ton standard coal increase in TC leads to an increase of CE by 0.001 ktCO2
k. Variable X10 = EG: 1 ton/one hundred million IDR increase in EG leads to an increase of CE by 275.728 ktCO2

Based on the regression model and the influence of each variable (change based on the variable unit) at the city level in Indonesia, it can be seen that the variables that have the most significant influence on increasing carbon emissions include EG, SG, and GP. On the other hand, the variables that affect reducing carbon emissions are ER, and the variables that do not directly affect changes in carbon emissions are TA and TG.

3.5. Cities classifications based on spatial and socioeconomic characteristics

The spatial and socioeconomic characteristics affecting CO_2 emissions and sequestration make the 32 cities in Indonesia be classified into several groups. This grouping can facilitate the provision of group-based recommendations and suggestions to increase the potential contribution to national climate mitigation efforts. The characteristics can be divided into subclasses based on each parameter.

a. Spatial: larger natural sphere (SpI) and larger built environment (SpII)

This classification divides cities based on the area of built-up areas and their natural areas. Cities with wider natural areas can be classified into the larger natural sphere (SpI), while cities with larger built areas are included in the larger built environment (SpII) group. The SpI group includes A1, G1, J3, K1, M2, M3, M4, P1, P2, P3, P4, P5, S1, S3, and T1. While SpII consists of B1, B2, B3, B4, B5, D1, J1, J2, K2, M1, M5, M6, P6, P7, S2, S4, and Y1. The grouping refers to the ratio of the area of the natural environment to the built environment. If more than 50 % is a built environment, it is included in SpII, and vice versa.

b. Social: highly urbanized city (SoI) and non-highly urbanized city (SoII)

Based on the social aspect, city group division includes highly urbanized and non-highly urbanized cities. A highly urbanized city (SoI) is a city that has a large population, while a non-highly urbanized city (SoII) is the opposite. The grouping of cities in Indonesia based on the population of big cities is 100,000–1,000,000 people, while more than 1,000,000 people are included in metropolitan cities. Therefore, So1 and SoII have a threshold of 1,000,000 people. If under 1,000,000, it is included in SoII, while if more than 1,000,000 people, it is included in SoI. So the cities in SoI include B2, B3, J1, M1, M6, P3, S2, and S4. The SoII includes: A1, B1, B4, B5, D1, G1, J2, J3, K1, K2, M2, M3, M4, M5, P1, P2, P4, P5, P6, P7, S1, S3, T1, and Y1.

c. Economy: greater economy (EcI) and weaker economy (EcII)

The division of Indonesian city classes based on economic conditions represented by GDP/GRDP per capita only consists of two groups: the greater economy and the weaker economy. Based on the Central Statistics Agency report for 2019, Indonesia's average GDP/GRDP per capita reached IDR 59.1 million. Therefore, this value can be used as a reference for dividing selected cities into these two groups. Cities with a GDP/GRDP of more than 59.1 million IDR will be included in the greater economy (EcI). On the other hand, cities whose GDP/GRDP is below 59.1 million IDR are included in the weaker economy (EcII). The EcI group consists of: B1, B3, B5, J1, J3, M1, M3, M6, P1, P2, P3, P4, P5, P6, P7, S1, S2, S4, T1, Y1. Cities included in EcII: A1, B2, B4, D1, G1, J2, K1, K2, M2, M4, M5, S3.

d. Technology: higher natural resources (TeI), highly industrialized (TeII), highly commercialized (TeIII)

The industrial sector includes three sub-sectors: primary, secondary, and tertiary. A higher natural resource (TeI) indicates a city that has a dominant primary industry and tends to utilize the available natural resources. Highly industrialized (TeII) represents cities that run more of the secondary industrial sector, which significantly converts raw materials into commodities. Meanwhile, a highly commercialized (TeIII) city dominates the tertiary industry sector, namely the market and non-market sectors. Based on the percentages, most selected cities are included in TeIII, which means they have strength in their tertiary industry. However, several cities are unique, with a higher percentage of secondary and primary sectors. Cities included in TeII, namely S2 and P6. While P3 has a ratio of the secondary industry that almost equals the tertiary industry, M2 has a percentage of the primary industry that is more remarkable than the secondary industry. However, P3 and M2 are still included in TeIII, like other cities not mentioned in TeII.

The classification above correlates with emissions and sequestration because each characteristic that becomes the parameter contributes to an increase or decrease in carbon dioxide emissions on a city scale. Each distinct group has its own tendency, both in emissions and sequestration. For example, cities in the SpI group tend to have higher sequestration rates than their emissions. While SpII tends to have a higher emission level than its sequestration. Another example is the tendency of the SoI group to emissions more than sequestration.

Conversely, the SoII group tends to have more sequestration than emissions. In the third group, EcI tends to have an emission level higher than the sequestration level, and EcII has an emission level lower than the sequestration level. Interestingly, the comparison in the fourth group related to technology is more difficult because the most selected city has a higher percentage of tertiary industries than primary and secondary industries. Based on previous studies, the primary industry tends to produce higher emissions but also has considerable sequestration potential because it can maintain carbon sinks from green or natural ecosystems [32]. Meanwhile, in previous studies, the secondary and tertiary industries produced emissions and negatively impacted the environment [32,33]. In Indonesia's city-level case, the secondary industry has the highest carbon emission impact, followed by the primary industry.

Combining these characteristics in one city can double emission levels, especially if the existing characteristics tend to accelerate the increase in carbon emissions. However, if each characteristic is combined but has contradictory tendencies, then it has the potential to offset the level of carbon emissions by increasing sequestration. For example, if a city has the characteristics of SpI, SoI, EcI, and TeI, then the characteristics of SpI and TeI will offset the negative tendencies of SoI and EcI. Therefore, to see emissions and sequestration, it is necessary to consider all characteristics as a whole because each of these parameters cannot be separated from one another.

4. Discussion

4.1. Policy implications

Indonesia aims to reduce emissions by 29 % with national ability or 41 % with international assistance in 2030 (in business as usual/BAU condition) and also targets net-zero emissions by 2060. Indonesia will encourage green development and low-carbon development by reducing emissions intensity from energy, land, waste, industry, and maritime sectors [34]. However, the issue of emissions in Indonesia is interrelated with local and multi-scale conditions, especially related to the energy sector and deforestation [35,36]. The Ministry of Environment and Forestry, headed by the Director General of Climate Change Control, handles climate change issues in Indonesia. Indonesia implements a tiered climate control process to support programs at the international level by ratifying some international programs and implementing national or central and regional policies [37].

The focus on handling climate change in Indonesia includes environmental, social, and economic sustainability. The three priorities focus on carbon and non-carbon benefits [38]. Even though the existing policies at the central level are very good, the implementation problems are crucial to Indonesia's low-carbon sustainable development [39]. One of Indonesia's community-based climate change mitigation policies is the Climate Village Program, which focuses on the smallest level of society, neighborhood unit, or the village level, by involving local communities as implementers. The climate village program is determined based on proposals, and the success of its implementation is highly dependent on the capacity of the implementers. The program's impact on a microscale is likely to be felt, but it tends to be less than optimal on a larger scale. Therefore, a similar program should be implemented at a larger, more complex level, like a city.

As a place where the population is concentrated, the city is a significant place to start implementing policies to tackle climate change. Cities in Indonesia have a crucial role in reducing emissions and increasing sequestration. The analysis results show that cities in Indonesia have very diverse spatial and socioeconomic characteristics, especially concerning emissions and sequestration. Several cities are significant contributors to emissions nationally, while several others are in a position where sequestration is greater than emissions. However, this situation is closely related to socioeconomic indicators in each urban area. Cities with good economic progress and development are likely to negatively impact efforts to reduce national emissions. In contrast, cities with the opposite condition positively contribute to carbon sequestration. Therefore, this issue is still a difficult choice.

The results of spatial mapping in selected cities show that emission and sequestration intensity locations are strongly influenced by natural elements, such as green areas (forests or vegetation) and blue regions (water). The spatial perspective of emissions and sequestration in Indonesian cities shows a tendency to reduce emission intensity and increase sequestration in areas with green and blue regions or locations adjacent to these areas. The spatial dimension of emissions and sequestration in this study can be a starting point in identifying potentials and challenges for Indonesia's urban carbon system to increase the quality and quantity of green and blue areas in each city. Indonesia is a tropical archipelago country where most of its cities are located on coastal waterfronts and still have rich vegetation that can help maximize the progress of national climate targets.

Policy implications based on the results of this study cover several aspects: spatial, social, energy, and lifestyle. The points included in the policy implications include:

a. Spatial policies: proportional and sustainable zoning and land use arrangements in urban areas; increasing the size of green spaces and natural areas; limiting the expansion of the urban regions (providing green buffer zones in suburban areas); building compact cities to reduce excessive land use; and maximizing the function and restoration of natural elements in urban areas.

b. Policies to restrict population numbers, reduce urbanization rate, and increase the attractiveness of rural areas through revitalization, and provide employment so that people's interest in living in villages increases and the pressure on urban areas can be reduced.
c. Policies to increase the use of renewable energy sources, increase the use of more effective and efficient public transportation, regulate industrial activities that apply sustainability principles, and use environmentally friendly and low-carbon technologies.
d. Policies that regulate or appeal to urban communities regarding lifestyles that can support national climate change mitigation targets include providing adequate facilities and infrastructures to support these lifestyles; starting a lifestyle that is sustainable and environmentally friendly at the individual, family, and collective levels on a larger community scale; and implementing policies that are coercive with a reward and punishment system.

Implementing these solutions can be carried out not only through policies regulated by the city government but also by the central government. Still, it can also be practiced at the community level in a smaller social group. The net-zero target must be started and supported by all levels of society, especially in urban areas.

4.2. Limitation of study

Many uncertainties exist in assessing carbon emissions at the city level [40]. Carbon emissions in cities are complex and influenced by many factors, and there is a possibility of contributors from the area around the city. Estimating carbon emissions at the city level based on driving factors provides aggregate output and does not sufficiently describe the spatial perspective of carbon emissions in detail. The ODIAC dataset, one of the sources of high-spatial resolution global emission data based on a grid map generated from satellite observed-nighttime lights and profiles (emission intensity and geographic location) of power plants, can provide a spatial perspective on carbon emissions [41]. The combination of factors-based estimation and grid maps can help reduce uncertainties in estimating carbon emissions while assessing the spatial and socioeconomic characteristics of a city's carbon emissions. Still, the availability, completeness, and accuracy of data at the city level are very influential, especially in studies involving multiple cities as the sample.

The study of spatial and socioeconomic characteristics in 32 representative cities is a preliminary study that can provide a general and multi-parameter picture of the condition of cities in Indonesia regarding carbon emissions and sequestration. However, this study has some limitations, which include case study areas and data selection. The selection of case study areas in the analysis is limited to large cities in some provinces in Indonesia, which are representative and have complete data availability. Due to data limitations, the newly formed provinces in Indonesia are not included in this study. The use of spatial emission data in this study uses data from ODIAC for 2019 as the latest data when the analysis begins, so other data is also the same year. However, 2019 data can also represent normal conditions before influential events, namely COVID-19, lockdown, and other events during the pandemic. In addition, the limited energy data on a city scale only relies on data from the electricity sector. However, energy use in Indonesia is still dominated by electricity compared to other energy sources. Therefore, the electricity sector is still quite representative of the energy sector at the urban level. Based on these limitations, follow-up and future studies can be carried out starting from this issue.

5. Conclusions

The carbon system, involving interactions between emissions and sequestration, plays an important role in climate change. Every level and sector tries to overcome climate change through mitigation, which cannot be separated from emissions and sequestration. In mitigating climate change, reducing emissions and increasing sequestration are the goals. Therefore, every effort to increase sequestration will automatically contribute to emission reduction efforts. Cities are starting points for mitigation, ranging from spatial to social and economic aspects. The status of carbon emissions and sequestration in important cities in Indonesia shows varied conditions. Most of the cities with the highest emission levels are located in Indonesia's western and central regions. The three largest cities in Indonesia: Jakarta, Surabaya, and Bandung have the highest carbon emissions levels. In contrast, the cities with the highest carbon sequestration levels are primarily located in Indonesia's eastern and central regions. Regarding the carbon balance index, only two cities are in ideal conditions, namely Mamuju and Manokwari, situated in Indonesia's eastern regions.

The spatial characteristics of carbon emissions in Indonesian cities are concentrated in the downtown area. As an archipelago country where most of its cities are located on waterfronts, carbon emissions reduction is also influenced by water bodies, such as rivers and seas. Meanwhile, the intensity of carbon sequestration is highly dependent on natural land cover. Based on socioeconomic characteristics, each driving factor has varying levels of influence on increasing and decreasing carbon emissions. The driving factors that have the most significant impact on carbon emissions in Indonesian cities are energy consumption per GDP, secondary industry, and GDP, which are then followed by the influence of other driving forces.

Selected cities can be classified under four parameters, with two to three sub-classes. These parameters include spatial, social, economic, and technological. Each interrelated group has positive and negative trends toward emission levels and sequestration performance. The combination of characteristics can balance each other, but it can also potentially increase sequestration or, in contrast, accelerate emissions. Characteristics that tend to encourage more carbon absorption must be maintained and improved, while factors that increase emissions must be managed and even limited.

Cities have great potential to achieve net zero targets and support climate crisis mitigation efforts. By starting at the city level, mitigation efforts are expected to be effective, efficient, and have a macro-impact on Indonesia nationally. Following the limitations of this study, further studies on this topic can expand the scope of analysis with more city samples for macro-scale or even country-level analysis. Future studies can also select only one representative area, but with a more in-depth analysis, and use timeframe-based data as a reference for future predictions related to carbon issues.

Data availability statement

Data will be made available on request.

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CRediT authorship contribution statement

Ainun Hasanah: Conceptualization, Data curation, Formal analysis, Methodology, Software, Validation, Visualization, Writing – original draft. **Jing Wu:** Conceptualization, Methodology, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2023.e22000.

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