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RESEARCH ARTICLE

Spatial Analysis of Urban Greenhouse Gas Emissions and Alternative Spatial Planning Policies for Low-Carbon Development in Jakarta Province

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ABSTRACT

Jakarta as the biggest metropolitan area in Indonesia, has contribute to the increasing amount of GHGs emissions due to rapid urbanization, transportation, industry, and energy consumption level. To facilitate low-carbon urban growth, spatial planning is essential, as it determines the distribution of emission sources according to land use. This research aimed to (1) measure and mapping the GHGs emissions and their distribution in Jakarta, (2) analyze the correlation between land use and emission level, (3) evaluate the effectiveness of the existing policies and regulations and formulate alternative strategies of spatial planning for low-carbon urban development in Jakarta. This research used quantitative and qualitative approaches with GIS-based spatial analysis, correlation analysis, policy gap analysis, and DPSIR (Driver-Pressure-State-Impact-Response) framework. The result showed that the total emissions in Jakarta increased from 20,769 thousand tons CO_2e in 2010, and reached the highest emissions in 2018, and then decreased and reached 29,266 thousand tons CO_2e in 2022. North Jakarta emitted the highest level of emissions, reaching 11,713 thousand tons of CO_2e. Based on correlation analysis, there is a strong correlation between emissions and the area of road infrastructure (R^2 = 0.9123), and a low correlation between emissions and residential area (R^2 = 0.369). The realization of the concept of low-carbon city can be implemented by doing spatial planning. A zoning-based approach can be applied to do spatial planning, where there are three categories of protected, strictly controlled, moderately controlled areas and emission reduction areas in order to achieve sustainable development and reduce carbon emission.

Introduction

Global environmental issues, such as the increasing of greenhouse gas (GHG) emissions into the atmosphere, global warming and climate change, are being studied to understand the impacts on sustainability of human life and ecosystems, as well as to understand the implications and work towards countermeasures. Although natural phenomena are a primary source of increased GHG concentrations, the levels are greatly accelerated by human activity associated with energy production and consumption, the transportation sector, changes to land and/or sea use including phenomena like land subsidence, among other things [1–3]. In terms of their relative contribution to the global increase in GHG emissions, urban areas where most economic activity occurs through high levels of energy consumption and mobility of the urban population, play a leading role in GHG emissions and thus the challenge of managing these emissions has become a key issue in urban emission management in order to mitigate climate change [4–7].

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The capital city of Indonesia, Jakarta has experienced tremendous growth from year to year not only in terms of business and industry, but also as a residential area for millions of people. The population of Jakarta has been recorded at 11.25 million with a growth rate of 0.92% per year. The city's density is as high as 16,700 people/km^2 with an area of 662.33 km^2 of which 91% have already transformed into built-up land [8]. In 2022, Jakarta's economic growth rate in 2022 reached 5.59% compared to the national average of 5.44% [8]. All these factors have imposed greater pressure on the environment caused by humans and resulted in a further increase in greenhouse gas emissions.

The capital city of Indonesia, Jakarta, recently has experienced an increasing trend of GHG emissions. The total direct emissions in Jakarta increase from 20,665 thousand tons of CO_2e in 2010 to 29,392 thousand tons of CO_2e in 2022. Meanwhile, the total indirect emissions also increased, reached 20,173 thousand tons of CO_2e in 2022 from 17,364 thousand tons of CO_2e in 2010 [9]. These emissions are mainly come from various sources i.e. power and fuel combustion from the several sectors such as industry, transportation, and others such as organic waste and industrial waste. This increase of GHG in urban area not only affect to the environment by increasing greenhouse effect and causes of environmental risks such as rising air temperature, changes of rainfall pattern that is expected can trigger hydrometeorological disasters, but also can trigger climate change that will face by the humankind [10,11]. With a very intense pace of infrastructure development and urban expansion in Jakarta, urban environment under pressure. Reducing and managing GHG emissions in a metropolitan city like Jakarta need a wider approach. It cannot only look into the sectoral approaches but also approach from sustainable spatial planning.

There is a growing global awareness that urban development must be low-carbon. Countries and cities around the world are incorporating their mitigation efforts into their urban development policies and making commitments to reduce greenhouse gas emissions through their nationally determined contributions (NDCs). In Indonesia, emission reduction targets have been established at the national level, while local governments, such as the Jakarta Provincial Government, are also developing their own low-carbon development policy. This study describes the development of Jakarta's low-carbon development policy based on Governor Regulation Number 90 of 2021 concerning the Climate-Resilient Regional Low-Carbon Development Plan (CRLCDP), which aims for a 50% reduction of greenhouse gas emissions by 2030 and net zero emission by 2050. The local governments play important roles in transforming the urban development into a lower emission system.

Spatial planning plays a crucial role in efforts to control GHG emissions because land use patterns influence the distribution of economic activity, population mobility, and energy consumption in urban areas [11–13]. Land use changes, particularly the conversion of green open spaces to built-up areas, not only reduce carbon absorption capacity but also increase emissions from construction activities and urban energy consumption [14–16]. Development patterns that tend to expand built-up areas without considering environmental capacity can exacerbate the impacts of climate change, such as increased urban temperatures and flood risk [17–20]. Therefore, integrating emission control into spatial planning policies is a crucial approach to low-carbon urban development.

GHG emission inventory data plays a crucial role in providing a quantitative overview of the sources and magnitude of emissions in urban areas and serves as a basis for formulating climate change mitigation policies [20–23]. Analysis of the spatial distribution of emissions allows the identification of locations with high emission levels, allowing for more effective and targeted mitigation strategies. Furthermore, urban green space management plays a crucial role in reducing GHG emissions by increasing the carbon sequestration capacity of vegetation [24,25]. Approaches that integrate emission inventories with spatial land use analysis are becoming increasingly important in supporting the development of data-driven and area-based emission mitigation strategies.

Although various studies have addressed GHG emission inventories and the factors influencing their increase in urban areas, studies integrating emissions data with spatial analysis of land use to support spatial planning policy formulation are still relatively limited. Yet, understanding the spatial distribution of GHG emissions is crucial for understanding where emissions occur and the spatial characteristics that contribute to them [13,21,26]. This information can assist urban planners and policymakers to design more effective spatial management strategies in order to support low-carbon urban development. This research aims to analyze the intensity and spatial distribution of Global Warming GHG emission in Jakarta Province. It also intends to study the correlation between land use and the emission rate, evaluates the scope and impacts of the implementation of GHG emission reductions policies and projects, and formulates alternative concept and policies of spatial planning to support the development of low carbon city in Jakarta Province. The contributions of this research are in the concept and practice of spatial planning that utilizing data of emission and strengthening collaboration between development policies at sub-national level and global actions as global climate change mitigation efforts.

Materials and Methods

Study Sites

This research was conducted in several locations in Jakarta, the center of economic, government, politics and urbanization of Indonesia. Jakarta administrative area are divided into 5 administrative urban government, namely, North Jakarta, South Jakarta, East Jakarta, West Jakarta and Central Jakarta with regional characteristics dominated by lowlands with an average elevation of approximately 7 meters above sea level (Figure 1). Geographically, Jakarta located around latitude and longitude 6°12' S and 106°48' E, respectively and has high population density [8]. Nowadays, Jakarta is facing many environmental problems caused by the urbanization, increasing needs of energy, and frantic activities of land and air transportation including vehicles and aviation that produce a lot of greenhouse gas emissions which are considered as a main caused of global warming [27–29]. Jakarta with its unique urban land use and land cover (LULC) pattern makes the city region an interesting area to be analyzed spatially for the Global Warming Potential (GHG) of emissions and for making spatial planning on emission basis. This study was conducted from January 2023 to April 2024 at the city of Jakarta mainland, excluding the Seribu Islands.

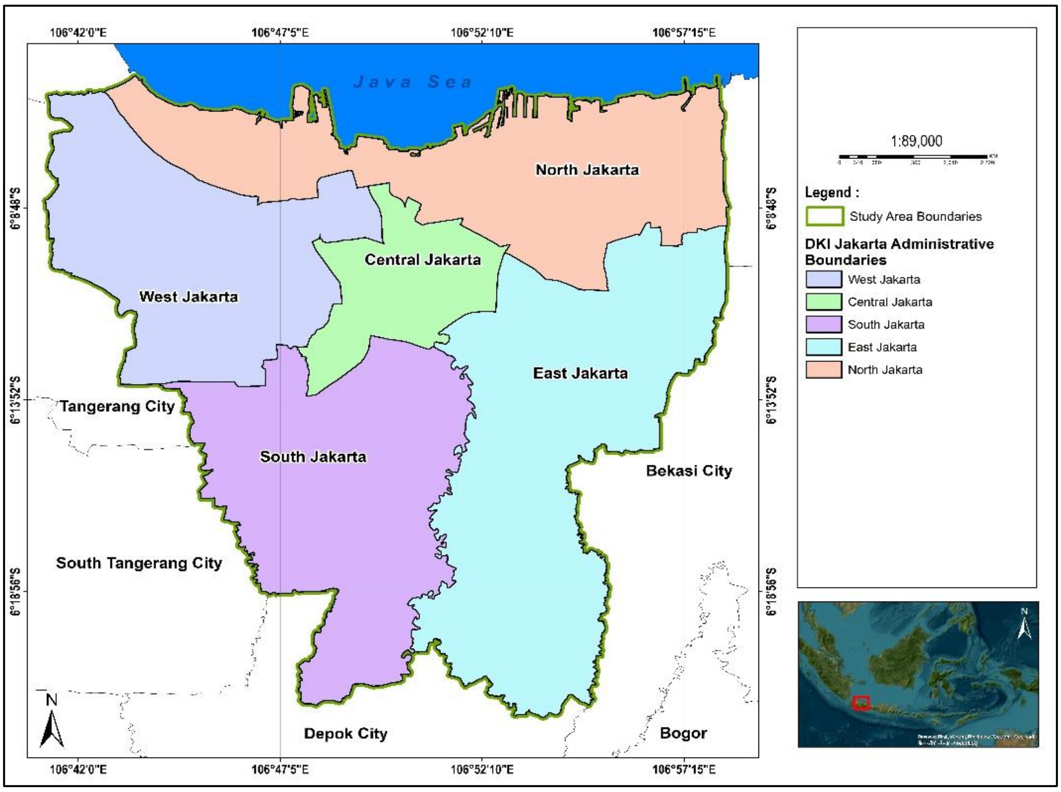

Figure 1. Map of Jakarta Province, Indonesia, showing five districts: West Jakarta, Central Jakarta, South Jakarta, East Jakarta, and North Jakarta.

Data Collection Methods

The use of primary and secondary data was employed to identify spatial distribution of GHG emission and land use practices associated with that emission in Jakarta Province. The secondary data consist of GHG emission inventory, regional administrative maps and spatial land use data. The selected data is greenhouse gas emission inventory data from Jakarta Provincial Environmental Agency for four years i.e. 2010, 2014, 2018 and 2022. The data is presented in the form of tons of CO_2 equivalent (tCO_2e) coming from the major sectors which emits greenhouse gases in urban area. The four years are chosen because there is availability and consistency of the used spatial land use data.

Data for land use spatial features was collected from the Jakarta one map portal, a system launched by the Jakarta Provincial Government to serve the purpose of sharing and consolidating all available data in the form of geospatial information for the purposes of supporting the planning and development of the region. In addition to land use, the portal contains other spatial data such as administrative boundaries and other spatial information. This research utilizes data from the portal for spatial analysis purposes. Official government portals are a good source of accurate and up-to-date spatial data that can be used as the basis of spatial-based research [21,22].

Even though secondary data was the main source of this research, it was supported by primary data. The primary data were collected by qualitative methods, namely by semi-structured interviews. The informants were selected by purposed sampling method, where the informants were officials from Jakarta Provincial Environmental Agency and academics who have expertized in the field of climate change and environmental management issues. The purpose of this interview was to seek information and to know about the implementation of policies on the control of GHG emissions and challenges in implementing low-carbon city development policies at the regional level.

Data Analysis Methods

Spatial Allocation of GHG Emissions

The GHG emission inventory obtained from the Jakarta Provincial Environmental Agency was originally compiled at the sectoral administrative level rather than at a spatially explicit, per-parcel resolution. Consequently, an additional spatial allocation procedure was required prior to any geographic analysis. This procedure was executed using a GIS-based emission mapping approach, wherein each recorded emission source was linked to its corresponding land-use category derived from the Jakarta one map geospatial dataset. Given the distinct physical characteristics of emission sources, two distinct allocation methods were applied. For emissions that come from specific sources like power plants and big industrial facilities, the pollution was linked directly to their exact locations on a map, without needing to break it down further into smaller areas. This allocation is expressed as:

$$E_p = E_{source} \quad (1)$$

where E_p represents the emission value attributed to point-source location p (in tCO_2e), and E_{source} denotes the emission value reported for that specific facility in the inventory. No areal disaggregation is required here because the precise location of the source is unambiguously known.

For area-source emissions, which are distributed diffusely across a land-use category rather than tied to a single point (e.g., emissions from residential activities, transportation networks, and commercial zones), a proportional disaggregation approach was adopted. These emissions were allocated according to the relative areal extent of each land-use polygon within the corresponding administrative unit:

$$E_i = E_k \times (\frac{A_i}{A_k}) \quad (2)$$

where E_i is the emission value allocated to land-use polygon i (in tCO_2e), E_k is the total area-source emission recorded for land-use category k within the administrative unit (in tCO_2e), A_i is the area of land-use polygon i belonging to category k (in km² or ha), and $A_k = \Sigma A_i$, which represents the total area of all polygons belonging to category k within the same administrative unit. This area-weighted disaggregation assumes a uniform emission intensity per unit area within a given land-use category, a standard simplifying assumption consistent with prior urban emission mapping studies [11,21,30].

Following the allocation of both point- and area-source emissions to their respective spatial units, the total emissions were aggregated at the administrative-city level and subsequently converted into an emission intensity metric to facilitate meaningful comparisons across regions of unequal geographic size:

$$I_i = \frac{E_j}{A_j} \quad (3)$$

where I_j is the emission intensity of administrative unit j (in tCO_2e/km^2), $E_j = \Sigma(E_p + E_i)$ represents the total emissions allocated to administrative unit j after summing all point- and area-source contributions (in tCO_2e), and A_j is the total land area of administrative unit j (in km²). Normalizing emissions by area prevents larger districts from appearing disproportionately high-emitting solely due to their geographic extent, thereby reflecting the actual emission density per unit of land, a metric directly relevant to spatial planning decisions.

GIS-based spatial analysis

We used ArcGIS 10.8 to do all the spatial processing and geoprocessing work. To make sure everything worked together seamlessly, we broke down the analysis into three steps. First, we prepared the emission inventory, land-use data, and administrative boundary datasets. Then, we made sure they were all compatible with each other. Finally, we did the spatial comparison. This approach ensure that all the different datasets could be used together accurately. To get everything to match up, the maps of administrative boundaries, land use, and emission inventory datasets were all converted to the same coordinate system. This was important because when you're working with different sources of data, the boundaries of the polygons might not quite line up. So, these discrepancies were fixed by making some geometric adjustments. This step is really crucial because even tiny mistakes in the boundaries can lead to big errors in the calculations, like the ones described in Equations (2) and (3).

To break down emissions by land use and location, we combined the land-use data with the administrative boundary information. This was done using a spatial overlay analysis in ArcGIS, where we intersected the two layers to link each land-use area with its location and emission value. This step allowed us to see how emissions vary across different land uses and regions. By doing this, we can get a better understanding of where emissions are coming from and how they are distributed across the area. The analysis involved using vector overlay operations, such as intersect and spatial join, to bring together the land-use and administrative boundary data. This enabled us to allocate emission values to each land-use area based on Equation (2), and ultimately, to disaggregate emissions by both land-use type and administrative region.

To calculate emissions are in different areas, we used a formula to calculate something called emission intensity for each part of the land and type of land use. We then grouped these intensity values into five categories, from very low to very high, using a special statistical method called natural breaks. This method helps us create groups that are as different from each other as possible, while making sure the things within each group are as similar as possible. This statistical optimization technique determines class boundaries by minimizing intra-class variance while maximizing inter-class variance. The method's performance is evaluated using the goodness of variance fit (GVF) (Equation 4).

$$GVF = \frac{(SDAM - SDCM)}{SDAM} \tag{4}$$

where *SDAM* is the sum of squared deviations of all observed values from the overall array mean, and *SDCM* is the sum of squared deviations of the values from their respective class means, summed across all classes. The Jenks algorithm iteratively adjusts class break points to maximize the GVF; a value approaching 1 indicates well-separated and internally homogeneous classes. This method was selected over equal-interval classification because emission intensity data typically exhibit a right-skewed distribution, with a small number of very high-emitting outliers (e.g., power plants and industrial zones) that would otherwise distort class boundaries under simpler classification schemes.

Statistical analysis of land use and emissions

The relationship between land-use characteristics and GHG emissions was quantitatively assessed using both pearson correlation and simple linear regression analyses. Land-use area (in hectares) was treated as the independent variable (x), while total GHG emissions (in tCO_2e) served as the dependent variable (y). The Pearson correlation coefficient was calculated as:

$$r = \frac{[\Sigma(x_i - \bar{x})(y_i - \bar{y})]}{\sqrt{[\Sigma(x_i - \bar{x})^2 \cdot \Sigma(y_i - \bar{y})^2]}} \tag{5}$$

where x_i is the land-use area of observation i (in ha), $\bar{x}$ is the mean land-use area across all observations, y_i is the GHG emission value of observation i (in tCO_2e), and $\bar{y}$ is the mean GHG emission value across all observations. To further characterize the predictive relationship, a simple linear regression model was fitted:

$$\hat{y} = a + bx \tag{6}$$

where the slope $b = \Sigma(x_i - \bar{x})(y_i - \bar{y}) / \Sigma(x_i - \bar{x})^2$ represents the estimated change in emissions per unit change in land-use area, and the intercept $a = \bar{y} - b \cdot \bar{x}$. The strength of this predictive relationship was evaluated using the coefficient of determination:

$$R^2 = 1 - \left(\frac{SSE}{SST}\right) = \frac{\Sigma(\hat{y}_i - \bar{y})^2}{\Sigma(y_i - \bar{y})^2} \tag{7}$$

where *SSE* is the sum of squared errors (residuals) between observed and predicted values, and *SST* is the total sum of squares of observed values around their mean. For a bivariate linear regression, R^2 is equivalent to the square of the Pearson correlation coefficient ($R^2 = r^2$). Thus, for example, $R^2 = 0.9123$ for road infrastructure, meaning that there is a strong predictive relationship between the amount of road area in a city and the total amount of emissions from that city, whereas $R^2 = 0.369$ for residential area, indicating a very weak predictive relationship. All statistical tests in this study have been performed at the level of significance of $\alpha = 0.05$. That is, any statistical relationship between variables in this study that are greater than chance is significant at the 95% confidence level, meaning that the probability of the results occurring by chance is less than 5%. These results indicate a strong relationship between the spatial distribution of a city's land use and the city's urban carbon emissions. The distribution of both human activity and energy consumption in a city is fundamentally spatial, i.e., defined by the city's layout or structure. Prior studies have established a relationship between a city's land use and its urban carbon emission levels [19,20,31].

Gap analysis and DPSIR assessment

The effectiveness of implemented GHG emission reduction policies was systematically evaluated using a gap analysis approach, which compared the actual emission reduction performance of each mitigation action against an ideal policy target [32]. For each intervention, the percentage emission reduction (%ER) was first calculated as:

$$\%ER = \left[\frac{(E\_baseline - E\_mitigation)}{E\_baseline}\right] \times 100 \quad (8)$$

where *E_baseline* is the baseline (business-as-usual) emission level for a given mitigation action (in tCO_2), and *E_mitigation* is the emission level after implementation of that action (in tCO_2). To ensure a consistent and reproducible evaluation, the observed %ER for each action was translated into an ordinal actual performance score (*Score_actual*) using a defined rubric: a score of 100 was assigned for reduction rates ≥95%; 75 for rates between 75% and 94%; 50 for rates between 50% and 74%; 25 for rates between 25% and 49%; and 0 for rates below 25%. These scores were then compared against an ideal score of 100, representing full achievement of the policy target. The normalized implementation gap was subsequently derived as:

$$Gap = \frac{(Score\_ideal - Score\_actual)}{Score\_ideal} \quad (9)$$

These are to indicate the extent of effective implementation, i.e., how far a policy target has been implemented, relative to an 'ideal' target (see above for details). In other words, the value of Gap equals to 0 means that a policy has been fully implemented, i.e., landfill mining program has been fully implemented with %ER of 100%, whereas composting program has been almost fully implemented with %ER of 99.6%. In contrast, a value of gap equals to 1 means that a policy has not been implemented at all, i.e., rooftop solar program has not been implemented with %ER of 0%, whereas solar street light program has not been implemented with %ER of 0%. A value of gap less than 0.5 means that a policy has been implemented effectively, whereas a value of gap greater than or equal to 0.5 means that a policy has not been implemented effectively, thus there are 'gaps' between a policy target and effective implementation and thus such policies need to be improved.

Building on the above analyses, this final section applies the DPSIR (Drivers–Pressures–State–Impact–Response) framework, a conceptual analytical framework that organizes evidence in a causal sequence, as opposed to generating numbers in a computation. Urbanization, population growth, and economic growth are the drivers of the high levels of GHG emissions in Jakarta. These drivers exert pressures on the urban environment, leading to increasing energy use, transport, and land use. The spatial distribution and intensity of the resulting GHG emissions form the State of the urban environment. These in turn give rise to climate change impacts, including increased flood risk, exposure to sea level rise, and high urban temperatures. The above analysis generated a range of responses, with the proposed emissions-based spatial zoning being the principal Response to the above impacts.

The DPSIR framework provided a conceptual basis for the spatial zoning policy in Jakarta Province. The principal drivers influencing GHG emissions in Jakarta included urbanization, growing population and rapid economic growth. These factors created increasing pressures upon the urban environment through growing demand for energy and for motorized transport as well as large-scale conversion of land to purposes of urban development. The spatial distribution and quantity of GHG emissions represented the environmental state. Climate change-related impacts upon Jakarta included increased vulnerability to flooding, exposure to sea-level rise along the North coast of Jakarta and the associated impacts of increased urban temperature. The spatial zoning policy proposed for emissions-based zoning of Jakarta Province was the principal Response proposed in this study in order to mitigate adverse environmental impacts. The DPSIR framework, widely applied in environmental policy analysis, identified and inter-related a sequence of influencing factors including human activity, environmental pressures, the resulting environmental state, impacts and responses

(DPSIR) [33–36]. Thus, the framework was used in this study in order to provide, on the basis of a wide range of associated spatial data and findings from the preceding analytical quantification of GHG emissions, a sequence of findings from a diagnostic spatial analysis which were, in turn, developed into a zoning policy for low-carbon urban development in Jakarta Province.

Results and Discussion

Results

Spatial Distribution of GHG Emissions

Using four-year emission data (2020, 2014, 2018, and 2022), an integrated GIS analysis was conducted to determine the spatial distribution of GHG emissions in Jakarta Province. The analysis results show that North Jakarta has the highest emission levels and Central Jakarta has the lowest (Figure 2 and Table 1).

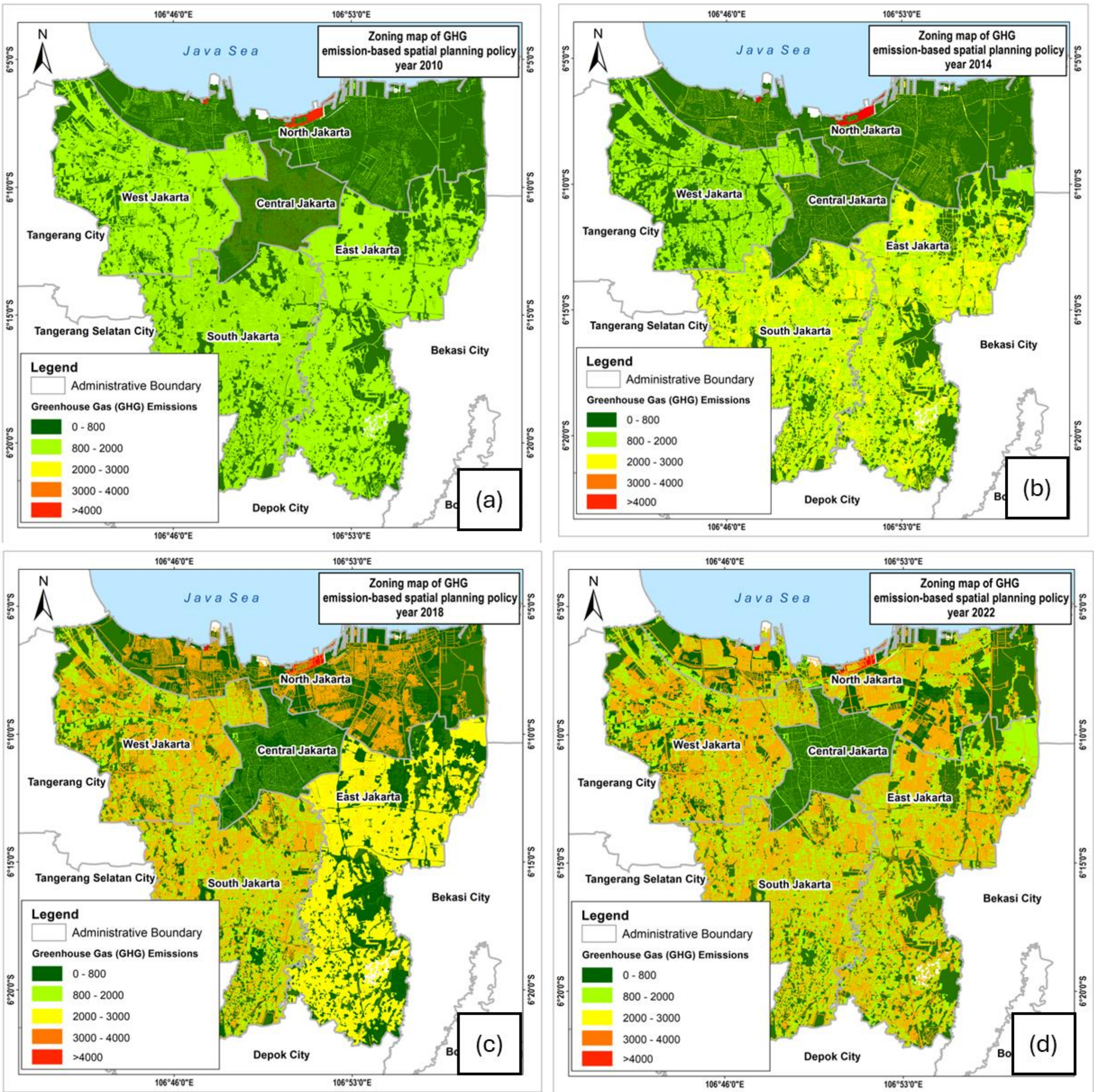

Figure 2. Comparison of GHG inventory distribution in Jakarta Province in (a) 2010, (b) 2014, (c) 2018, and (d) 2022. This figure presents a spatial map of the distribution of GHG emissions in Jakarta Province over a four-year period. Between 2010 and 2022, Jakarta showed an increase in GHG emissions across various regions. North and East Jakarta were the two administrative cities with the highest emissions due to high land use intensity for economic activities and power generation.

Table 1. Jakarta GHG Emission Values based on administrative cities. GHG emissions of each administrative city in Jakarta Province in 2010, 2014, 2018, and 2022 can be seen in thousand tons CO_2 eq. This table presents an increasing trend in emissions across all regions from 2010 to 2018 and a slight decline in 2022. North Jakarta always ranks highest in GHG emission values compared to other regions, while Central Jakarta always ranks lowest.

Sector emissions	Emission value (thousand tons CO_2 eq)			
	2010	2014	2018	2022
East Jakarta	3,202	4,305	5,712	5,500
North Jakarta	10,435	11,328	12,390	11,713
West Jakarta	2,809	3,364	4,985	4,751
South Jakarta	3,095	4,043	5,417	5,186
Central Jakarta	1,229	1,617	2,220	2,117
Amount	20,769	24,657	30,725	29,266

Relationship Between Land Use and Emissions

The relationship between land use and GHG emissions was analyzed using correlation analysis of land use types and the number of emissions generated in the study area. The analysis results indicate that some land use types contribute significantly more to emissions than others. The results of the correlation analysis between land use and GHG emissions are shown in Figure 3 and Table 2.

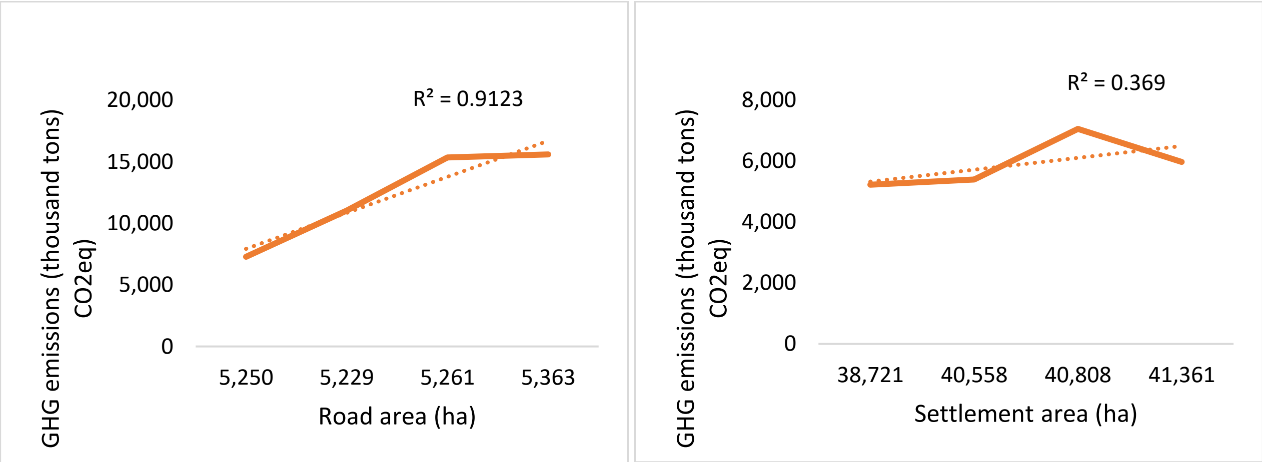

Figure 3. Graph of the relationship between land use and GHG emissions. This figure displays the relationship between land use area, namely road area and residential area, and GHG emissions measured in thousand tons of CO_2 equivalent over several observation periods. The left graph shows the relationship between road area and GHG emissions indicating a very strong correlation (r^2 = 0.9123). Meanwhile, the right graph shows the relationship between residential area and GHG emissions reflecting a weaker correlation (r^2 value = 0.369).

Table 2. Results of the correlation analysis between land use and GHG emissions.

Type of land use	Emission value (thousand tons CO_2 eq)			
	2010	2014	2018	2022
Lake	0.0	0.0	0.0	0.0
Sea pier	2.6	4.4	5.8	5.8
pond	4.6	4.6	4.6	4.6
Building/construction	162.4	158.9	324.6	428.7
Mangrove forest	0.0	0.0	0.0	0.0
Road	7,283.5	11,043.5	15,340.7	15,599.4
Land sand/dunes	0.0	0.0	0.0	0.0
Sand/sea dunes	0.0	0.0	0.0	0.0
Power plants	8,044.0	8,010.0	7,938.0	7,212.0
Plantation/garden	0.6	0.5	0.5	0.5
Settlements & activity places	5,227.4	5,394.2	7,059.8	5,971.1
Overlapping properties	34.3	33.8	43.9	36.8
Swamp	0.0	0.0	0.0	0.0

Type of land use	Emission value (thousand tons CO_2 eq)			
	2010	2014	2018	2022
Ricefield	1.6	1.5	1.5	1.5
Shrubs	0.0	0.0	0.0	0.0
River	0.0	0.0	0.0	0.0
Fishpond	7.1	4.7	4.7	4.7
Bare/bare land	0.0	0.0	0.0	0.0
Dry fields/fields	0.8	0.8	0.8	0.8
Other non-cultivated vegetation	0.0	0.0	0.0	0.0
Amount	20,769.0	24,657.0	30,725.0	29,266.0

Evaluation of Emission Reduction Policies

The evaluation of the implementation of GHG emission reduction policies in Jakarta Province was conducted through a gap analysis between established policies and implementation conditions on the ground. The evaluation results indicate that policy implementation has not been fully effective in significantly reducing GHG emissions. The results of the GHG emission reduction policy gap evaluation are presented in Table 3.

Table 3. Results of the gap analysis of GHG emission reduction policies. This table presents a comparison between baseline emission levels, post-mitigation emission levels, remaining emissions, and the percentage reduction in emissions for various mitigation actions implemented in each sector. The results of performance assessments are presented through actual scores, ideal scores, and gap values as indicators of policy effectiveness. These data reflect the implementation of various emission reduction strategies in an urban context with primary emission sources from power generation, transportation, and waste management.

Mitigation action	Baseline emission level (tons CO_2)	Mitigation emission level (tons CO_2)	Remaining emissions (tons CO_2)	Percentage of emission reduction rate (%)	Scoring	Ideal score	Gap
Energy (Power Plant)							
Energy efficiency at the Muara Karang Power Plant.	4,944,350	3,367,510	1,576,840	68.1	50	100	0.5
The use of rooftop solar power plants in government buildings, schools, commercial buildings, households and communal solar power plants.	16,313	0	16,313	0.0	0	100	1
Clean energy development: waste-to-energy plants and LFG-fueled power plants	8,981	155	8,826	1.7	0	100	1
Substitution of fuel oil with gas at the Muara Karang Power Plant and Tanjung Priok IP	10,830,339	7,993,732	2,836,607	73.8	50	100	0.5
Use of biofuels in industrial subsectors	1,090,151	768,484	321,667	70.5	50	100	0.5
Introduction green buildings in commercial buildings	138,176	106,340	31,836	77.0	75	100	0.25
Energy conversion in government buildings	9,709	1,036	8,673	10.7	0	100	1
Use of LHE for street lights	430,136	238,930	191,206	55.5	50	100	0.5
Use of PJU TS	113	0	113	0.0	0	100	1
Transportation							
Transportation Management through the implementation of ITS systems	668,057	579,801	88,256	86.8	75	100	0.25
Busway	3,416,013	713,336	2,702,677	20.9	0	100	1
Feeder Busway	5,556,561	2,244,321	3,312,240	40.4	25	100	0.75
Use of electric trains	207,021	75,363	131,658	36.4	25	100	0.75
Use of MRT	3,457	1,354	2.103	39.2	25	100	0.75
Use of Biofuel	736,316	15,557	720,759	2.1	0	100	1
Use of CNG	55,322	44,885	10,437	81.1	75	100	0.25
Waste							
LFG Recovery at Bantar Gebang Landfill	1,481,324	1,443,989	37,335	97.5	100	100	0
Composting organic waste	1,481,324	1,474,840	6,484	99.6	100	100	0
3R paper activities	1,481,324	1,426,471	54,853	96.3	100	100	0
Pilot Project for Waste-to-Energy Plant (PLTSa) at Bantar Gebang and Maggot TPSTs	1,481,324	1,478,418	2,906	99.8	100	100	0
Landfill Mining	1,481,324	1,481,266	58	100.0	100	100	0
On-Site Wastewater Treatment (WWTP)	1,103,165	1,099,265	3,900	99.6	100	100	0
Off-Site Liquid Waste Treatment (LWTP)	1,103,165	1,102,590	575	99.9	100	100	0

Based on the analysis of spatial distribution of emissions, land use relationships, and policy evaluation, this study also identifies the causal relationship between urban development activities and increased greenhouse gas emissions using the DPSIR framework. This framework is used to understand the driving factors of emissions, pressures on the environment, the conditions of emissions that occur, the resulting impacts, and the policy responses needed to control greenhouse gas emissions in the Jakarta Province. The results of the DPSIR analysis are presented in Figure 4.

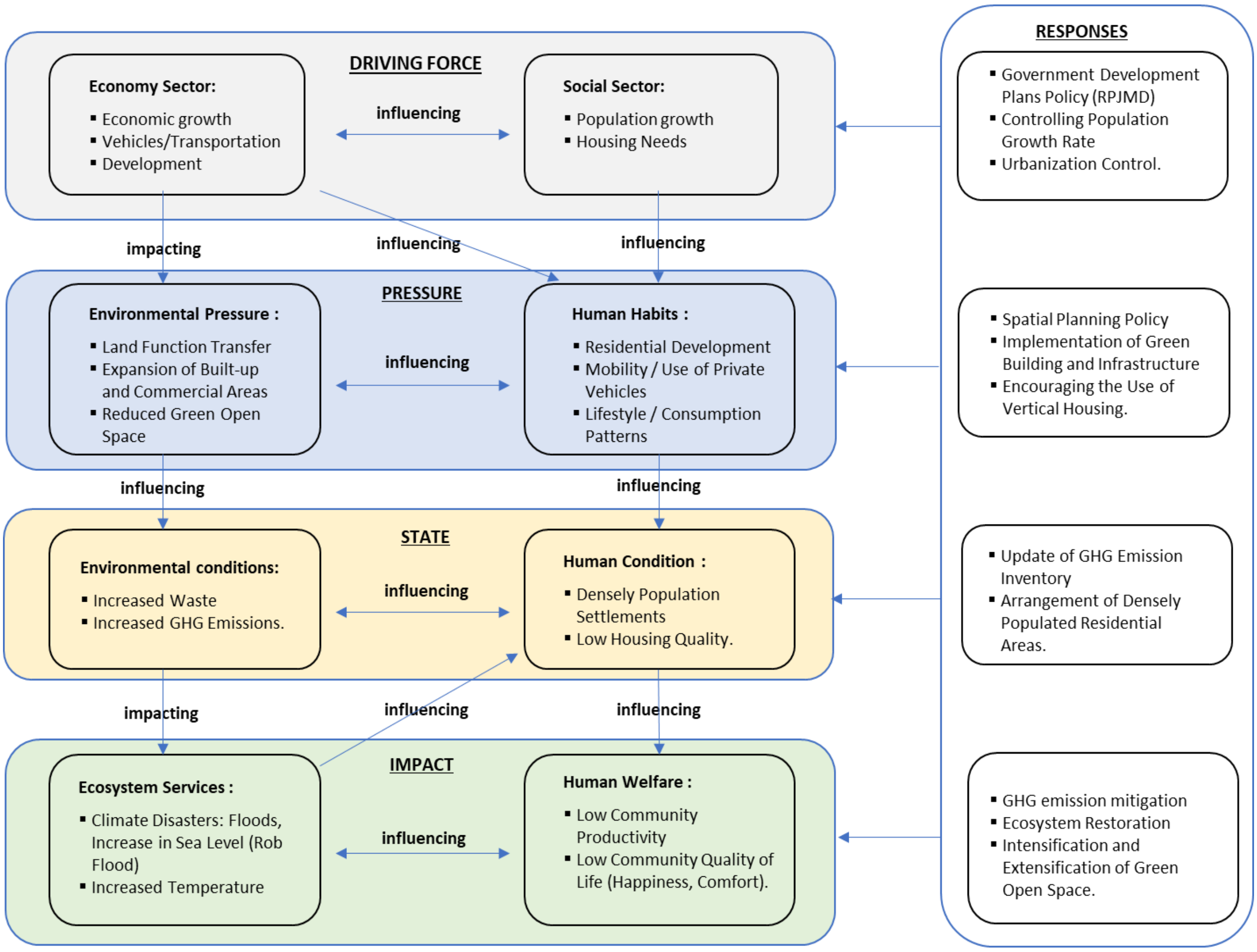

Figure 4. The evaluation of GHG emission reduction policy using the DPSIR approach. This figure illustrates the causal relationship between driving factors (economic and social sectors), pressure (environmental pressures and human habits), state (environmental and human conditions), and impacts on ecosystem services and human welfare.

Alternative Spatial Planning Policies

Based on the analysis of the spatial distribution of emissions, land-use relationships, and policy evaluations, this study formulated alternative spatial planning policies to support low-carbon city development in the Jakarta Province. This study proposed an emissions-based spatial planning zoning approach consisting of four area categories: protected areas, strictly controlled areas, moderately controlled areas, and emission reduction areas. A zoning map of the emissions-based spatial planning policy is presented in Figure 5.

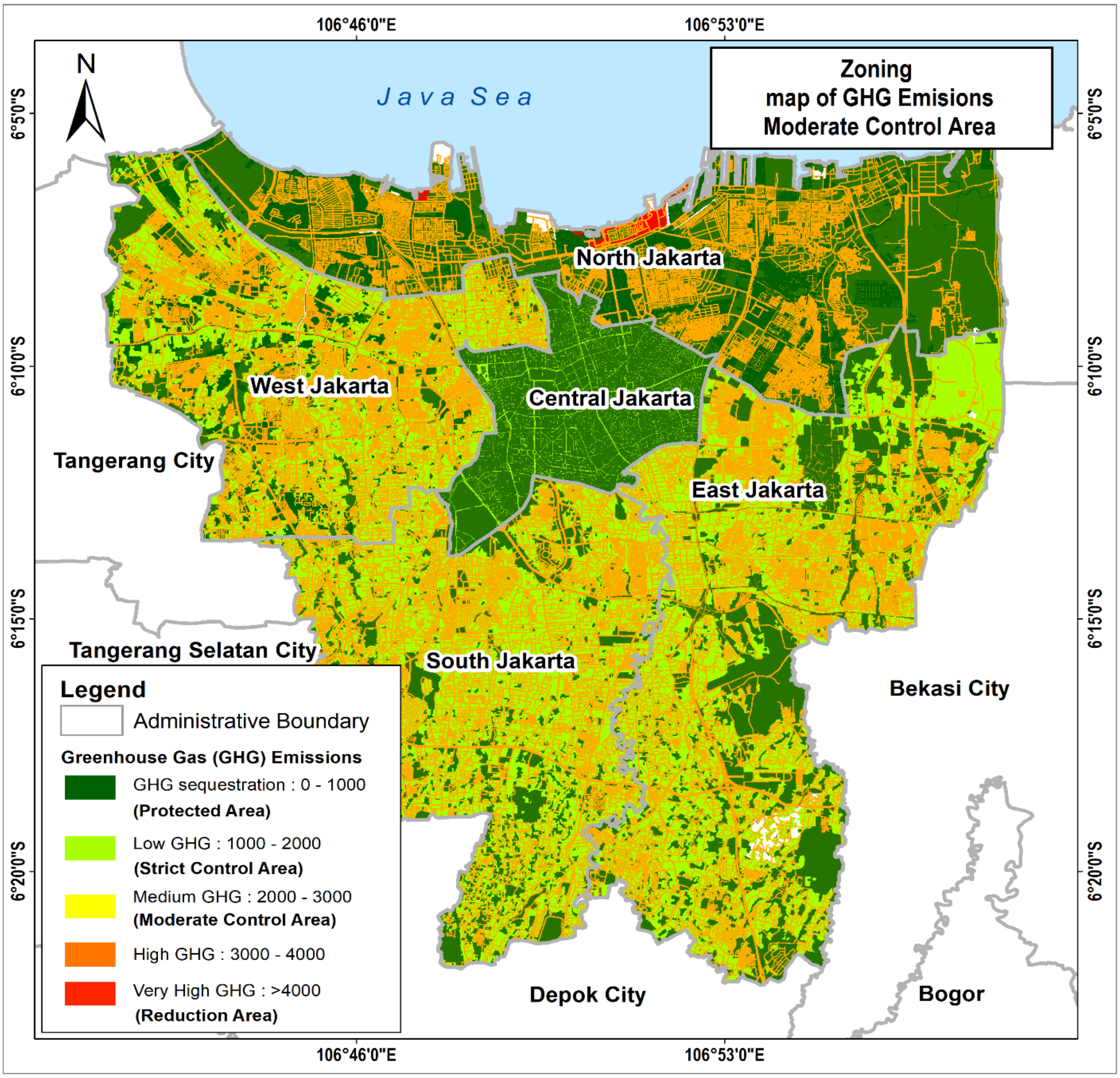

Figure 5. Zoning map of GHG emission-based spatial planning policy. This figure displays the spatial distribution of GHG emissions classified into five categories based on the magnitude of emissions: very low (0 – 1,000 tonnes CO_2e), low (1,000 – 2,000 tonnes CO_2e), medium (2,000 – 3,000 tonnes CO_2e), high (3,000 – 4,000 tonnes CO_2e), and very high (> 4,000 tonnes CO_2e).

Discussion

Spatial Distribution of GHG Emissions

The analysis showed that the distribution of greenhouse gas emissions in Jakarta Province exhibited an uneven spatial pattern across administrative regions. High economic activity and dense energy infrastructure drive increased GHG emissions, as reflected in the high GHG emissions in North Jakarta. The presence of power plants, port activity, and dense transportation routes contribute to this administrative city's position as the region with the highest GHG emissions in the Jakarta Province. Conversely, Central Jakarta has the lowest GHG emissions, supported by its land use pattern with abundant green open space, despite the area's relatively high building density. The above conditions are supported by various theories stating that economic activity contributes significantly to carbon emissions [13,23]. Urban development patterns and transportation systems also influence carbon emissions [21,23]. Therefore, spatial-based analysis is expected to depict the distribution of GHG emissions to help decision-makers identify priority locations for carbon emission reduction at the city level.

Relationship Between Land Use and Emissions

Correlation analysis results indicated that some land-use types contributed significantly more to emissions than others. Road infrastructure, residential areas, and power generation facilities are the main contributors to GHG emissions in Jakarta Province. This indicates that the land-use structure in urban areas significantly influences emission levels. These findings are consistent with various studies showing that changes in land use and urban development patterns are closely linked to increased carbon emissions [6,15,16,37]. Areas with high levels of human activity tend to produce higher emissions owing to increased energy consumption and transport. Conversely, vegetation and green open spaces play a crucial role in absorbing carbon, thus helping to reduce emission concentrations in urban areas [6,37,38]. The relationship between land use and GHG emissions demonstrates that emission controls in urban areas cannot be separated from urban spatial management policies. Integrating emission control into spatial planning policies can help direct urban development toward more efficient and low-carbon development patterns.

Evaluation of Emission Reduction Policies

An evaluation of greenhouse gas emission reduction policies in Jakarta Province shows that the effectiveness of policy implementation varies across sectors. Gap analysis is used to compare the level of policy implementation with desired ideal conditions. A gap value < 0.5 indicates that policy implementation is relatively effective and close to ideal conditions, whereas a gap value > 0.5 indicates a significant gap between policy targets and the ground reality. Various programs related to waste processing have had a significant impact on reducing GHG emissions. Waste sorting at source, liquid waste processing, and household waste processing in temporary landfills have reduced the volume of waste entering sanitary landfills. Meanwhile, government programs related to energy diversification, such as rooftop solar, biofuels, and the development of energy-efficient mass transportation systems, still face numerous challenges and have not yet shown a significant impact. These challenges include infrastructure availability and intersectoral coordination.

Mitigating climate change in urban areas requires support from various parties and strong policies, given the complexity and significant environmental challenges in urban areas. Limited institutional capacity, urban dynamics, and budget constraints contribute to program implementation difficulties [12,22,30,31,39]. Therefore, intersectoral coordination, along with strategies in energy, transportation, and regional planning, is crucial for controlling GHG emissions in metropolitan areas. The DPSIR analysis also shows that the increase in GHG emissions in Jakarta is rooted in urbanization, increasing human population, and increasing economic activity. These three factors put pressure on the urban ecosystem, ranging from increased energy consumption, changes in land use, to the use of motorized vehicles. GHG emissions also impact climate change, triggering natural disasters such as flooding and sea level rise on the Jakarta coast. North Jakarta, as an administrative city bordering the sea, is highly vulnerable to these threats. Good policy integration is expected to improve adaptation strategies for areas with high disaster vulnerability to climate change.

Alternative Spatial Planning Policies

The link between the spatial distribution of GHG emissions, land use, and policy demonstrates the importance of regional planning strategies to support low-carbon urban development in the Jakarta Province. This strategy emphasizes the use of spatial distribution data on GHG emissions to incorporate them into regional planning policies. Good regional planning considers not only economic and social aspects but also the environment as a pillar of sustainability. The results of the spatial analysis divide regional zones into four categories based on GHG emissions: protected (areas with potential carbon sinks such as mangrove forests, green open spaces, and water bodies), strictly monitored, moderately monitored, and emission reduction areas. These zones are determined based on the spatial distribution of GHG emissions. However, these four zones require ecosystem rehabilitation and protection, as well as the enhancement of carbon sink areas, to reduce damage and degradation of ecological functions.

Areas with the highest GHG emissions, such as industrial areas, power plants, and dense transportation areas, are categorized as strictly monitored zones. These zones are recommended to improve energy efficiency, implement green building standards, and develop environmentally friendly transportation systems. The development of compact cities accompanied by the use of environmentally friendly energy is expected to reduce GHG emissions in these zones. Moderate monitoring areas are characterized by medium emission levels, which are dominated by residential areas and other urban activities. Policies that can be implemented in these zones include developing more efficient public transportation, increasing energy efficiency in buildings, and developing compact city concepts that can reduce the need for private vehicle mobility. In emission reduction areas, policies focus on developing low-carbon technologies, increasing the use of renewable energy, and optimizing green open spaces to balance the emissions generated by urban activities. This emissions-based spatial zoning approach demonstrates that spatial planning can serve as a strategic instrument to support climate change mitigation in urban areas. To create urban areas that are adaptive to climate change, spatial analysis of GHG emissions is essential inserted in urban planning policies.

Conclusions

Spatial analysis shows that North Jakarta has the highest GHG emissions of the five administrative cities, while Central Jakarta has the lowest. Land use is closely related to GHG emissions, as indicated by high GHG emissions in areas with high economic activity, dense transportation systems, and land use for power plants. These findings demonstrate the importance of integrating regional planning policies with spatial analysis related to emissions as a strategy for the development of low-carbon urban areas. With proper zoning, the government can adjust policies based on different zoning related to GHG emissions. By integrating GHG emission inventory data into the spatial planning process, the government is expected to be able to create policies that are adaptive to climate change, thereby strengthening the synergy between regional development and emission reduction targets at the national and global levels.

Author Contributions

PAW: Conceptualization, Methodology, Data curation, Formal analysis, Investigation, Visualization, Writing - Original Draft & Editing; **SRPS**: Supervision, Methodology, Validation, Writing - Review & Editing; **IKD**: Supervision, Validation, Writing - Review & Editing; **LFA**: Investigation, Data curation; **PAP**: Investigation, Data curation; and **GM**: Investigation, Data curation.

AI Writing Statement

During the preparation of this work, the authors used ChatGPT (OpenAI) to assist in improving language clarity and organizing the manuscript structure. After using this tool, the authors carefully reviewed and edited the content as necessary and took full responsibility for the accuracy and integrity of the publication.

Conflicts of interest

There are no conflicts to declare.

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