Research Paper

Multi-Scale Analysis of Urban Density and Carbon Emission Dynamics

A Case Study of Harbin, China (2007-2021)

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Abstract

Global urbanization accelerates economic development but also poses significant environmental challenges. As urban expansion continues, the coexistence of high-density central areas and low-density fringes raises a critical issue in urban planning: balancing density distribution with environmental sustainability. This study examines Harbin, a typical expanding city in Northeast China, to analyze the dynamic changes in spatial structure and carbon emissions during urban expansion. By exploring the complex relationship between urban density and carbon emissions at different spatial scales, it provides insights for sustainable development with reduced environmental impact. This study uses multi-source data, combining statistical analysis and nighttime light imagery, to investigate urban density and carbon emissions in Harbin. The results show that: From 2007 to 2021, Harbin's total carbon emissions significantly increased, especially in central and fringe areas, indicating a spatial clustering effect. Compact urban development promotes low-carbon urbanization. The detailed block-scale analysis revealed that the effect of increasing density on reducing carbon emissions diminishes beyond a certain threshold. These findings underscore the critical role of density in sustainable urban development. The study also provides guidance on density management strategies to support sustainable urban planning.

Keywords

Sustainable urban density, Carbon emission dynamics, Urban Expansion, Multi-Scale analysis

1. Introduction

With the acceleration of global urbanization, spatial and population growth have driven economic development but also increased risks to urban society and the environment. Approximately 80% of global greenhouse gas emissions are estimated to originate from cities, which are centers of human activity, industrial production, transportation, and construction, characterized by high energy consumption and carbon emissions (Liu and Qin, 2016; Dhakal, 2009). Against the backdrop of rapid economic development in China, urban expansion has introduced new pressures on sustainable urban development. Issues such as dispersed land use, inadequate supporting services, and ecological pollution have emerged during urban expansion(Schuster-Olbrich et al., 2024), contributing significantly to urban carbon emissions. Sustainable urban development is a critical issue for cities globally.

Rapid urban expansion has led cities into a phase of high-density development, increasing resource and environmental constraints. The coexistence of high-density central areas and low-density urban fringes presents a pressing challenge to balance urban density distribution with environmental sustainability.

It has been shown that urban density is one of the key factors influencing carbon emissions (Hong et al., 2022). Dense cities are generally considered to be more resource-efficient and sustainable than sparse cities (Kumar and Sen, 2025). Previous have examined various drivers of carbon emissions, such as urban economic development, land use, industrial structure, and urban form (Wang et al., 2016; Martínez-Zarzoso et al., 2011). Existing studies on urban density and carbon emissions usually adopt two perspectives: one is a macro-scale study on cities or urban agglomerations that explores the relationship between population density and carbon emissions (Gudipudi et al., 2016; Hong et al., 2022), and the other is a micro-scale study on spatial density in the built environment, which mostly focuses on residential areas (Du et al., 2024). These two types of studies have their own focus, but due to the differences in research areas, research scope, and research methods, it is more difficult to form a systematic research conclusion. The combination of multi-scale research, from macro to micro, top-down systematic analysis, can make up for these shortcomings, and more effectively put forward research conclusions with guiding significance (Luo et al., 2024).

A systematic analysis of the impact of urban density on carbon emissions requires a macro to micro estimation of carbon emissions. Nighttime light data show greater potential for this type of study (Shi et al., 2016). Previous estimation methods based solely on statistical data could only achieve provincial-scale estimates, making it difficult to achieve comparisons of spatial differences between regions. The advent and application of nighttime light hassolved this problem. Nighttime light can better reflect the intensity of social and economic activities in cities. It is often used to conduct research related to urban sprawl patterns and spatial distribution of carbon emissions, and is now accepted as a representative feature of urban carbon emissions (Shi et al., 2016). This method is able to simulate the relationship between the value of nighttime light and total carbon emissions through a linear regression model, which simulates the spatial distribution of carbon emissions in different areas of the city based on the intensity of nighttime light in the city (Wu et al., 2024). Therefore, the method plays an important role in solving the estimation of carbon emissions from macro to micro level, and can systematically reveal the evolutionary trend of the spatial distribution of urban carbon emissions.

This study uses a typical sprawling city in northeastern China, Harbin, as a case study to explore the relationship between density and carbon emissions in this type of city. Using nighttime light data, we analyzed urban spatial and carbon emission changes in Harbin, systematically analyzing and discussing the complex relationship between urban density and carbon emissions from the macro-urban level to the micro-block level. The results of the study provide insights into how to achieve sustainable development while minimizing the impact on the environment, and provide guidelines for density control in the urban planning process to promote low-carbon city building and sustainable development.

2. Study area and research methods

2.1. General situation and study area

Harbin, located in Heilongjiang Province in northeastern China, serves as the economic center of the region. Harbin represents cold-region cities in China, characterized by a temperate continental climate with low average temperatures, long winters, and short summers. Consequently, winter heating energy consumption in Harbin is high. As a resource-based city, Harbin's carbon emissions are moderate compared to other Chinese cities, creating pressure to achieve energy conservation and emission reductions.

As of 2023, Harbin's total urban area covers 53,076.4 km^2. As a typical city in northeastern China, Harbin has experienced significant spatial expansion in recent years. The construction of large-scale, low-density new urban areas has posed new challenges for managing urban density. Due to historical and cultural factors, Harbin's central area contains extensive Russian-style historical zones and large industrial legacy areas. These areas, developed many years ago with high density, contrast sharply with newly constructed areas. Currently, urban renewal in old districts and new area development are underway. Balancing density management in these areas to achieve low-carbon and emission reduction goals is a pressing challenge for Harbin.

This study focuses on Harbin's built-up area, using a 15-year longitudinal analysis from 2007 to 2021, considering data availability and spatial transformation characteristics. This period captures Harbin's major urban expansion and subsequent stabilization, allowing effective examination of changes in urban spatial structure and carbon emissions. Figure 1 shows the location of Harbin.

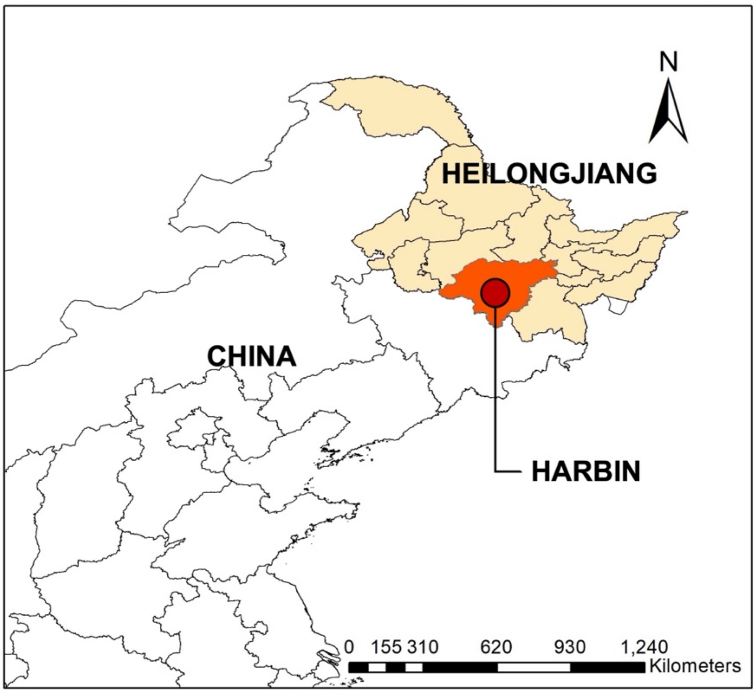


Figure 1. The location of Harbin.

2.2. Carbon emissions estimation

Harbin's carbon emissions were calculated using its energy consumption statistics. We determined carbon emission factors for various energy sources (coal, natural gas, oil, electricity, etc.) based on IPCC Guidelines for National Greenhouse Gas Inventories (2006) (Zhang et al., 2023). We calculated carbon emissions from five key sectors: buildings, transportation, industry and mining, municipalities, and carbon sinks. These are the sectors that previous studies have shown to be significant contributors to the city's overall carbon emissions and energy consumption. We aggregated the energy use of each sector within the built-up area and applied the relevant carbon emission factors to estimate the carbon emissions of the sector.

Total carbon emissions are calculated by adding up the emissions from these sectors for the year, for a total of 15 years of data from 2007-2021. This 15-year study period covers the rapid expansion of the city and the subsequent stabilization of the city's development, enabling a comprehensive assessment of the time-varying characteristics of Harbin's carbon emissions as a result of the city's development.

2.3. Nighttime light analysis

Nighttime light imagery analysis is widely used as a spatial method for estimating carbon emissions (Chen et al., 2021). Nighttime light images can visualize the distribution of artificial light sources in the city and can effectively represent human activities (Fang et al., 2022). There has been extensive research demonstrating the ability of nighttime light imagery to assess GDP, energy use, or population density. The initial nighttime light images were from the Defense Meteorological Satellite Program's Operational linescan system (DMSP-OLS). Since 2011, a new generation of night-time light data, NPP/VIIRS, sensed by the Visible Infrared Imaging Radiometer Suite (VIIRS) carried by the Suomi National Polar-Orbiting Partnership (Suomi NPP) satellites, which has higher radiometric and spatial resolution, has been operational.

This study requires continuous annual nighttime light imagery data from 2007-2021. Therefore, we use a long time series nighttime light data obtained by synthesizing DMSP-OLS and NPP/VIIRS after oversaturation correction and timing correction, which solves the problem that these two sets of nighttime light data can not be used at the same time (Chen et al., 2021). This dataset has parameter attributes consistent with the NPP-VIIRS nighttime light data and has similar data quality. The accuracy of this data is 500-meter resolution.

In order to systematically simulate the spatial distribution of carbon emissions and the process of change using nighttime light images, we developed a linear regression model for the total digital number value of nighttime light and carbon emissions. Linear regression is a widely adopted approach in similar studies. This model estimated carbon emissions based on nighttime light intensity, simulating emissions across different spatial locations within Harbin's built-up area. Using this method, we obtained the spatial distribution and temporal variation of carbon emissions in Harbin from 2007 to 2021.

2.4. Multi-Scale Density analysis

Density has long been a crucial factor in urban sustainability studies. Many studies have confirmed a relationship between density and carbon emissions. However, the mechanisms and extent of density's influence on carbon emissions vary across different spatial scales. Therefore, this study uses a multi-scale analysis to explore the complex relationship between density and carbon emissions at both city and block levels.

At the city level, we conducted spatial structure analysis to examine the impact of density on carbon emissions from a macro perspective. We used ArcGIS to analyze urban expansion and spatial trends in carbon emissions in Harbin's built-up area from 2007 to 2021. We also calculated changes in urban density during expansion and assessed their effect on total carbon emissions. Urban density was measured using two indicators: population density and urban spatial compactness, with their formulas provided below.

At the block level, we selected 20 representative blocks in Harbin as study samples. Our focus at this scale was to analyze the density differences across different types of blocks and how these differences influence carbon emissions at a more localized scale. Building density and floor area ratio were used as indicators to assess block density. These indicators are commonly used in block-scale studies and are suitable for discussing density differences in greater detail.

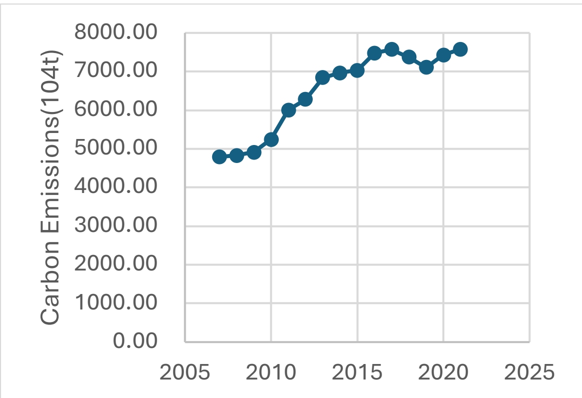
3. Results

3.1. Carbon emissions estimation results

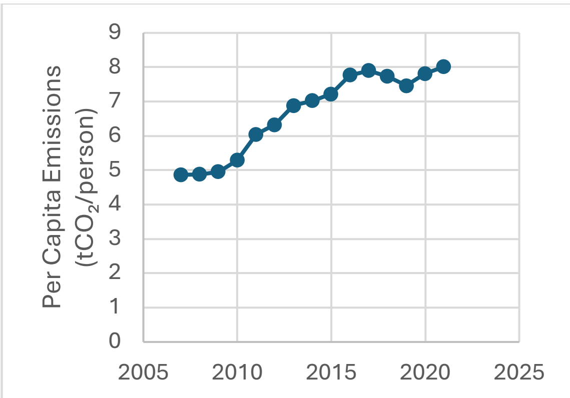
Using energy usage statistics for Harbin's built-up area, we estimated carbon emissions from 2007 to 2021 and conducted a preliminary analysis. We analyzed the temporal trends in carbon emission intensity from three perspectives: total carbon emissions, per capita carbon emissions, and carbon emissions per unit of GDP. We then examined the characteristics and changes in carbon emissions across various sectors in Harbin over the 15-year period.

As shown in Figure 2a, total carbon emissions showed an overall increasing trend, with significant growth observed before 2018, reaching a peak in that year. After 2018, total carbon emissions stabilized. Per capita carbon emissions also showed an upward trend, with a particularly rapid increase from 2010 to 2015 (Figure 2b). In contrast, as shown in Figure 2c, carbon emissions per unit of GDP declined significantly over the 15-year period, with the most pronounced decrease between 2007 and 2012, indicating more carbon-efficient economic growth over time. Between 2012 and 2018, emissions per unit of GDP remained relatively stable with minimal change.

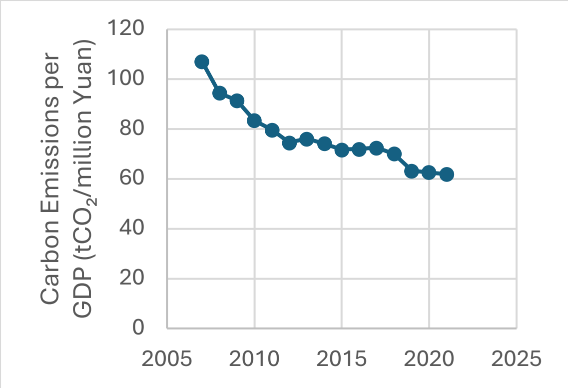
Finally, Figure 2d shows the four main sectors contributing to emissions: buildings, transportation, industry, and municipal services. The results indicate that industrial carbon emissions consistently accounted for the largest share. Transportation emissions also represented a substantial proportion, especially between 2011 and 2017. Overall, while industrial emissions remained stable, other sectors showed fluctuations.



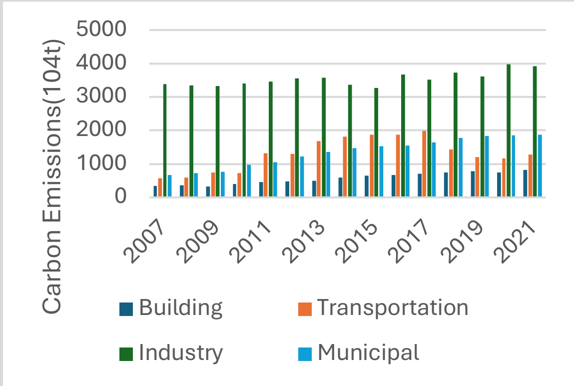
(a) Annual Total Carbon Emissions



(b) Per Capita Carbon Emissions



(c) Carbon Emissions per Unit of GDP



(d) Carbon Emissions by Sectors

Figure 2. Carbon Emission Analysis of Harbin.

3.2. Nighttime light analysis results

Nighttime light imagery analysis reveals the spatial distribution of carbon emissions in Harbin. Compared to simple time series analysis, this approach provides insights into the dynamic spatial evolution of carbon emissions within the built-up area of Harbin. To facilitate observing changes in carbon emissions, we categorized emissions into four levels: High-CE, Mid-high-CE, Mid-low-CE, and Low-CE. Figure 3 shows the spatial distribution changes of carbon emissions in Harbin's built-up area from 2007 to 2021.

The results indicate that in 2007, high carbon emission areas were concentrated in the central urban area. With urban development, High-CE areas expanded and transformed from a single large cluster into multiple dispersed clusters, indicating a shift in Harbin's urban structure from monocentric to polycentric development. Mid-high-CE areas expanded slightly as the city developed but remained stable after 2013. Mid-low-CE areas accounted for the largest proportion of Harbin's built-up area, mainly expanding at the urban fringe. Low-CE areas were mainly concentrated at the urban periphery, showing edge expansion. This pattern reflects Harbin's urban expansion, where construction at the urban fringe led to the emergence and growth of Mid-low and Low-CE areas. Since the urban fringe is in early development, characterized by low construction and population densities, energy consumption and carbon emissions are relatively lower compared to the city center. This does not necessarily mean these areas are genuinely low-carbon.

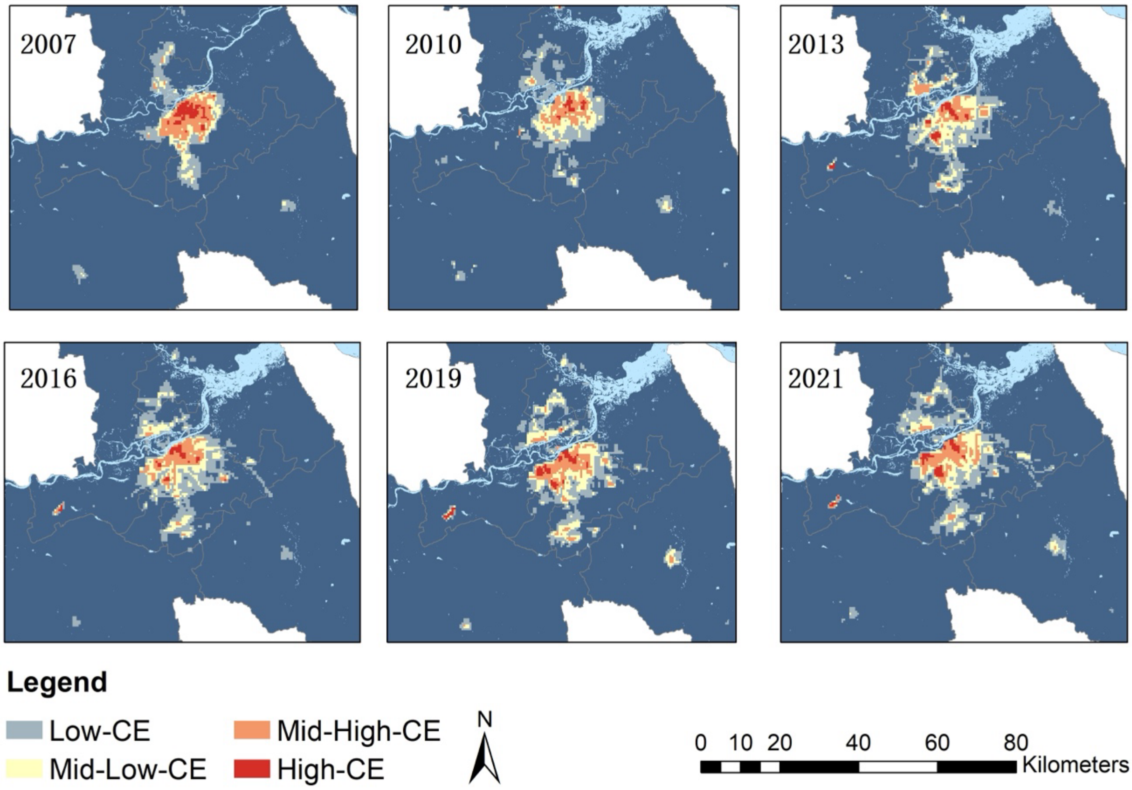


Figure 3. Changes in the spatial distribution of carbon emissions in Harbin.

3.3. City-level spatial structure analysis results

The spatial structure analysis at the city scale focuses on the urban expansion trends in Harbin and the impact of changes in urban form on carbon emissions during the expansion process. Figure 3 also shows that, over the 15 years, the urban fringes of Harbin experienced significant outward expansion. This expansion was most pronounced between 2007 and 2013, with the largest expansion area and fastest growth rate during this period.

As mentioned earlier, this study uses population density and urban spatial compactness to measure urban density changes. Figure 4 shows the trends of these two indicators over the 15-year period. Harbin's population density showed an overall decline, with significant fluctuations before 2012. Urban spatial compactness followed a similar trend, with more pronounced fluctuations, especially before 2013. This confirms that Harbin experienced rapid, unplanned urban expansion from 2007 to 2013, resulting in inefficient land use.

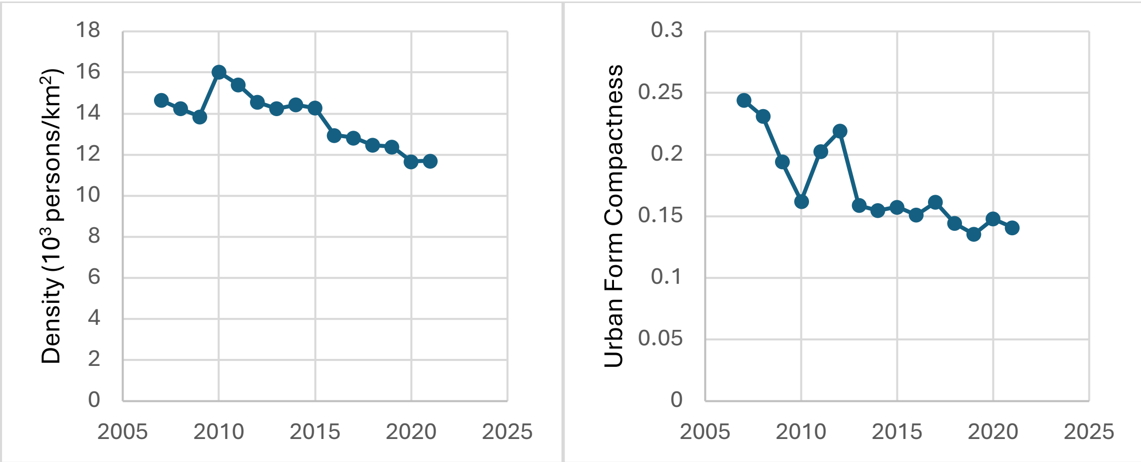


Figure 4. Harbin's density and urban form compactness change trends (2007-2021).

We conducted regression analyses of population density and urban spatial compactness against total carbon emissions to further explore the impact of density on carbon emissions. The results indicate that both population density and urban form compactness exhibit a negative nonlinear relationship with carbon emissions (Figure 5). At the city level, higher population density and greater urban compactness were associated with lower total carbon emissions. This confirms that high-density, compact development is beneficial for low-carbon outcomes at a macro urban scale. This effect may be attributed to increased efficiency in energy and infrastructure use in a compact urban form, and reduced energy costs for transportation, thereby lowering overall carbon emissions.

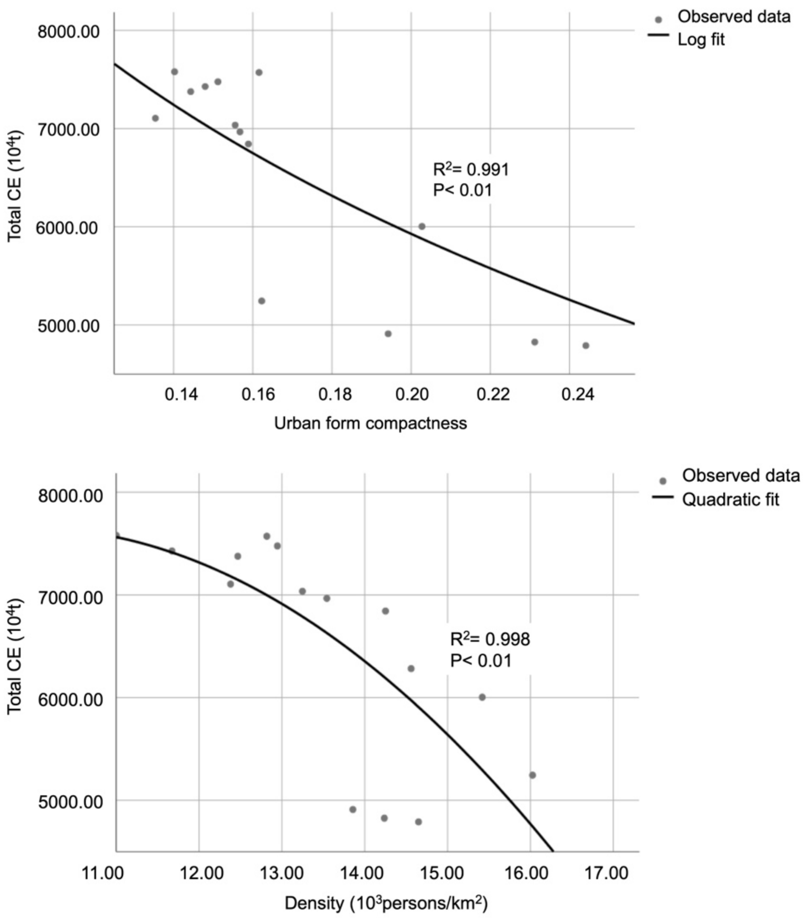
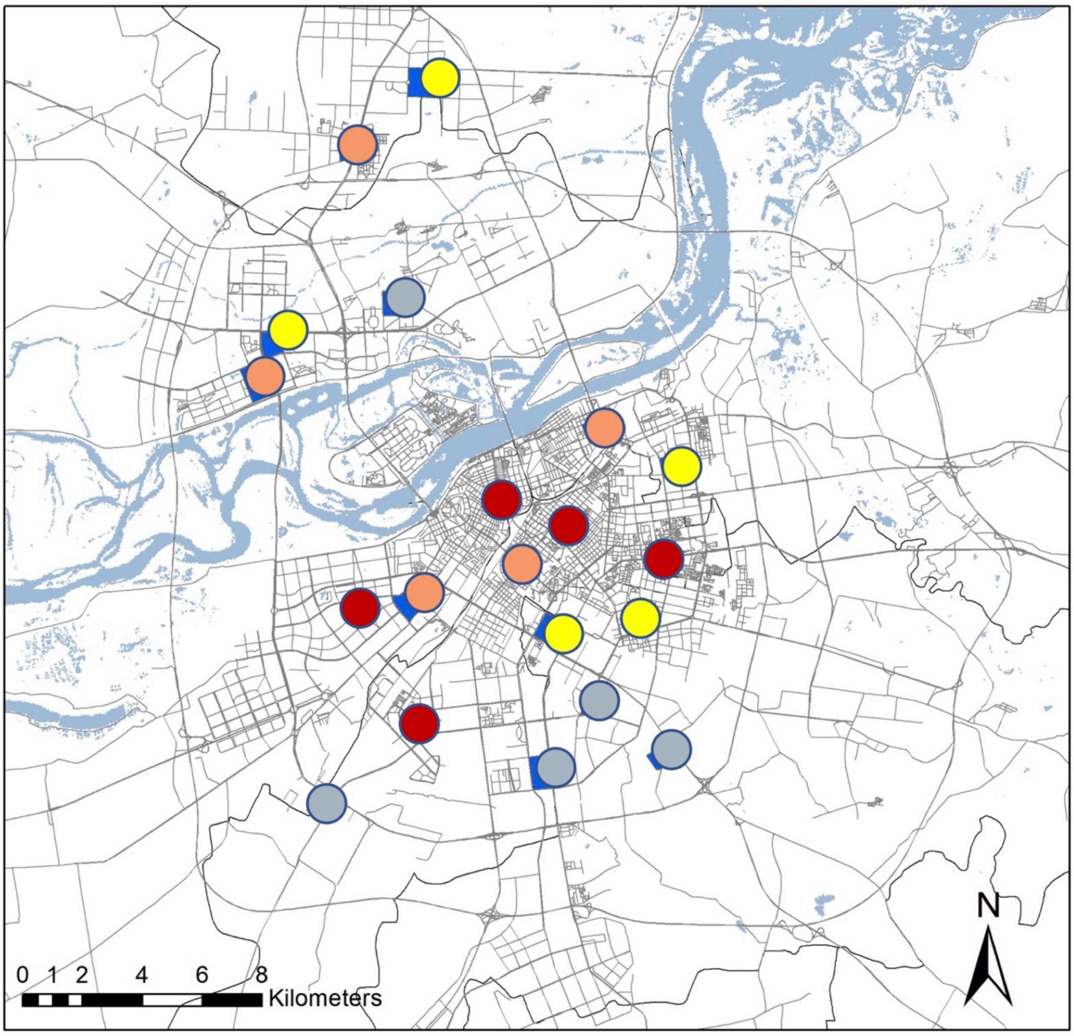


Figure 5. Relationships Between Total Carbon Emissions and Urban Density Metrics (Urban Form Compactness and Population Density).

3.4. Block-level density analysis results

In this study, we selected 20 blocks for block-level density analysis (Figure 6). Based on the carbon emission distribution in Harbin, we randomly selected five blocks from each of the four emission levels: High-CE, Mid-high-CE, Mid-low-CE, and Low-CE. As shown in Figure 6, these blocks are evenly distributed across the main urban area of Harbin, representing different parts of the city. Additionally, these blocks encompass various construction periods and urban form characteristics, making them representative for this study.



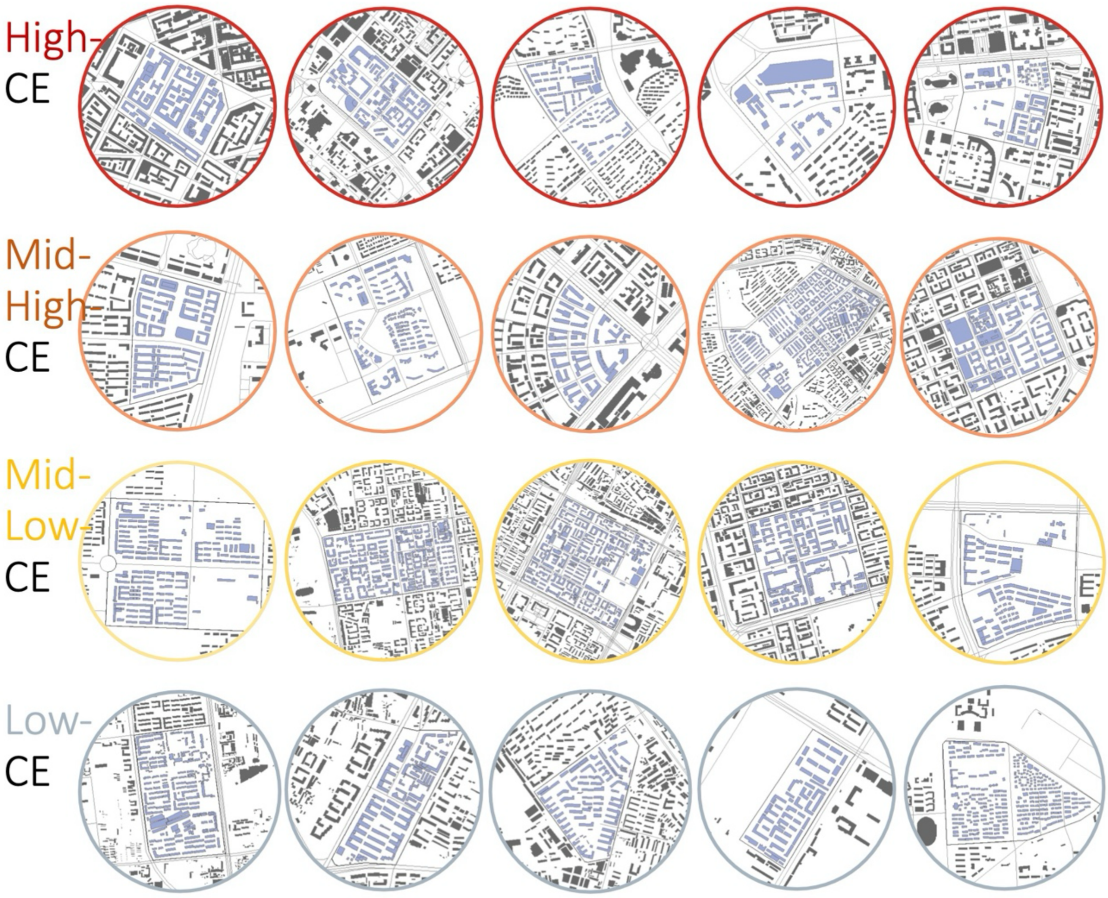


Figure 6. 20 block samples.

At the block scale, we used building density and floor area ratio (FAR) to measure density differences. The preliminary analysis of the block samples revealed large differences in density and urban form between new and older blocks in Harbin, as well as large differences between blocks in different parts of the city. Harbin's older blocks are generally located in the central areas of the city. They tend to have smaller block sizes, higher building densities and higher Floor Area Ratios. In contrast, newer blocks are usually found in the outskirts of the city or in newer areas of the city. These blocks are usually larger in scale, with lower building densities and relatively lower Floor Area Ratios.

In order to analyze the impact of these density differences on carbon emissions in more detail, we also conducted a regression analysis of block-scale density metrics with total block carbon emissions. The results showed that building density and floor area ratio were negatively correlated with total carbon emissions in a nonlinear relationship (Figure 7). Increased building density and floor area ratio were associated with reduced total carbon emissions. This may be because higher building density and floor area ratio indicate a more compact building layout. Compact layouts lead to more efficient land use and improved public transport accessibility, reducing total carbon emissions at the block level.

However, analysis of both building density and floor area ratio revealed a similar trend. When building density and floor area ratio reached a certain threshold, the reduction in carbon emissions began to slow. This may be because extremely high-density areas, beyond a certain point, create new environmental challenges that increase energy consumption and demand. For example, high-density environments lead to poor ventilation, increased cooling demand, and reduced green spaces, all contributing to additional energy consumption.

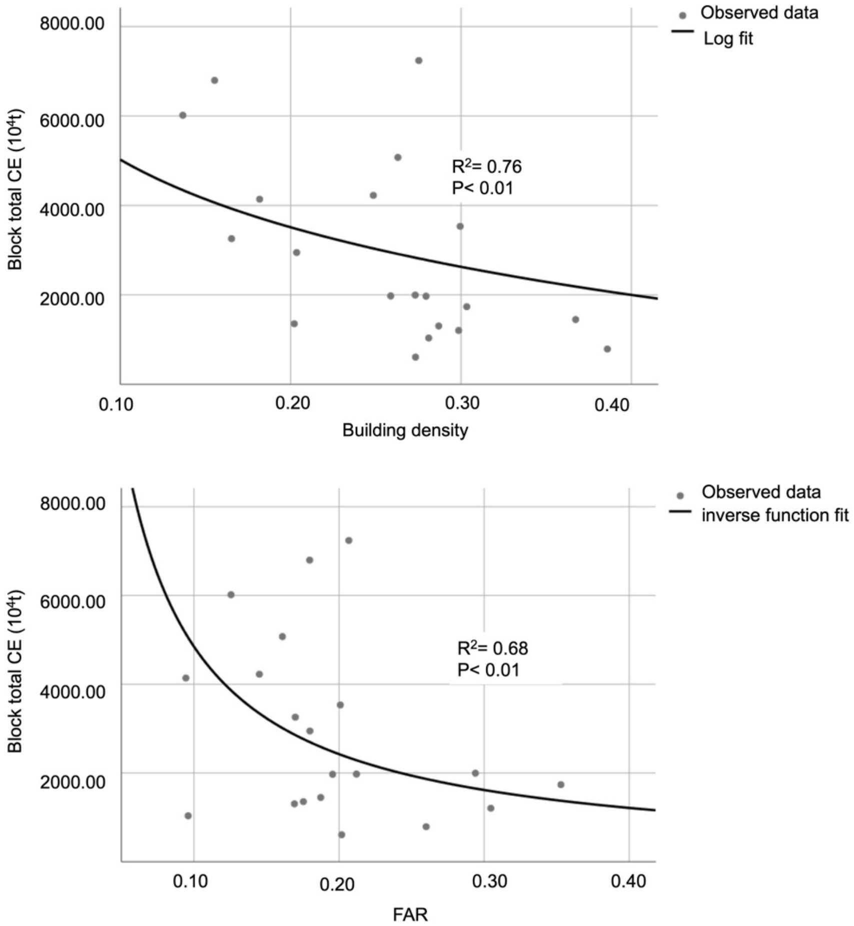


Figure 7. Relationships Between Total Carbon Emissions and Block Density Metrics (Building Density and Floor Area Ratio).

4. Conclusion

To systematically analyze the relationship between density and carbon emissions, this study used a multi-scale approach to examine the impact of density on carbon emissions from macro to micro perspectives. High-density, compact development helps reduce urban carbon emissions. However, at finer spatial scales, the effect of density on carbon emissions becomes more complex. Once density reaches a certain threshold, its impact on reducing emissions begins to diminish. This study emphasizes the role of density management in promoting sustainable urban development and provides strategic insights for urban density control.

We recommend delineating high-density, mid-density, and low-density control zones based on land use at the city level. Density management should be implemented at both the macro city and micro block scales, with targeted control measures for different functional zones. The concept of high-density, compact development should be consistently applied in urban planning, particularly in newly developed areas. For already developed areas, it is not feasible to apply the same density control measures as during initial construction. In these areas, emphasis should be placed on improving energy and resource efficiency, enhancing public transportation accessibility, and reducing carbon emissions while maintaining high density. Increasing green space and planting high-carbon sequestration vegetation in developed areas can create a better living environment while enhancing urban carbon sinks. Intelligent monitoring technologies should be used in urban management to monitor density distribution and carbon emissions in real-time, ensuring urban development aligns with sustainable principles.

Due to data limitations, this study has constraints in deeply exploring the impact of density distribution on carbon emissions. Additionally, many factors beyond density influence carbon emissions. Factors such as land use, road networks, and residents' behaviors are also important contributors to carbon emissions. In future research, we plan to incorporate these factors to develop more effective strategies for guiding urban planning to reduce carbon emissions and promote sustainable urban development.

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