Research Paper

Urban Carbon Emission Prediction and Carbon Neutrality Pathways Based on Urban Spatial Elements

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Abstract

Climate change poses a significant global threat, and achieving carbon peaking and neutrality has become a key urban development strategy in China. Carbon accounting is a crucial technique for monitoring urban carbon emissions and guiding low-carbon urban development. Defining the urban built-up area as the carbon accounting boundary and integrating carbon accounting and prediction with urban spatial elements is essential for achieving the "dual carbon" targets. This study focuses on Harbin, Heilongjiang Province, China, summarizing and analyzing 15 years of energy activity and spatial usage data. The study establishes an urban carbon accounting system and develops a prediction method using urban spatial activity data. The results are compared with energy use-based carbon accounting to verify the method's accuracy. Based on this, the study analyzes how different urban elements impact carbon emissions, offering technical support for urban spatial planning to achieve the "dual carbon" targets.

Keywords

Carbon peak and carbon neutrality; urban spatial elements; carbon accounting; carbon prediction

1. Introduction

Climate change in the 21st century has significantly impacted human activities and livelihoods. Promoting low-carbon economic and social transformations to address climate change has become a global consensus (Lynn *et al.*, 2021; Dhakal, 2009). As a result, 136 countries have set clear timelines for achieving carbon neutrality. Cities, as hubs of human activity, are major centers of energy consumption and carbon emissions. Therefore, in order to achieve carbon neutrality, developing low-carbon and sustainable urban development pathways is critical (Li *et al.*, 2022).

The balance between high-density urban development and the need for low-carbon, sustainable construction is critical to the achievement of carbon neutrality (B *et al.*, 2011). Accurate methods for predicting urban carbon emissions are important for identifying carbon-neutral pathways and supporting low-carbon development decisions. However, due to the limitations of carbon accounting and forecasting techniques, studies often lack direct relevance and guidance on specific carbon reduction techniques for urban areas.(Dhakal, 2009; D *et al.*, 2016). With the continuous development of research on spatial carbon accounting systems, new methods and perspectives for predicting urban carbon emissions have gradually emerged. The use of urban spatial data to predict carbon emission trends and the application of these findings to low-carbon development decision-making has become a key research area of great practical significance, with far-reaching implications for the realization of carbon neutrality.

Current urban carbon accounting and forecasting methods typically categorize regional emissions into four sectors: energy activities, industrial processes, agriculture and forestry, and waste treatment (Hoornweg *et al.*, 2011). Carbon emissions from each sector are calculated from energy activity data and ultimately aggregated into a total regional GHG emissions. The methodology has been widely adopted by countries around the world and is used by many cities and regions to calculate urban emissions, develop greenhouse gas emissions inventories, and project emissions changes (Li et al., 2022). Policymakers and researchers use these results to assess the impact of changes in energy use on carbon emissions and to monitor changes in the structure of urban emissions, making it the most widely used carbon accounting technique in urban planning (Steininger *et al.*, 2015). Despite the advantages of energy-based carbon accounting methods, their weak correlation with urban spatial elements leads to low correlation with spatial factors, insufficient feedback, interaction and support, and insufficient guidance for urban planning.

Strengthening the integration of carbon accounting and forecasting methods with urban spatial elements has become an important research direction. Scholars analyzed the spatial and temporal evolution and spatial distribution of urban carbon emissions using nighttime lighting data, and initially established the coupling relationship with urban spatial elements (Zhang *et al.*, 2023). An in-depth study on emission reduction mechanisms for urban and rural spatial development has established a "land use-carbon emission" framework based on categorization, inventory classification and emission reduction pathways. This framework integrates urban elements as core components of the carbon accounting method and has been applied in cities (Hu *et al.*, 2016; Huo *et al.*, 2022). Currently, urban spatial elements in research are relatively simple, mainly involving land use scale and average activity levels, while some critical activity data are challenging to obtain (Lin and Sun, 2010). Scholars have proposed a universal urban spatial carbon emission accounting and prediction method using the national greenhouse gas inventory framework, combining energy consumption data with urban land-use data to establish a research framework focused on industry, buildings, transportation, and carbon sinks (Li et al., 2022). Based on this, they developed a comprehensive carbon emission assessment framework for urban master plans, encompassing all natural resource elements and validated with Wuhan as a case study (Zhang *et al.*, 2021; Yang *et al.*, 2016; Raciti *et al.*, 2014). Significant progress has been made in developing urban spatial carbon emission accounting methods. Although these methods typically consider the entire city and account for emissions from all urban spatial elements, they are most effective in urban areas with large-scale construction and high development intensity (Bhatt *et al.*, 2023). For cities dependent on agriculture and mineral resources, the accounting results often lack accuracy and fail to reflect their development levels accurately. Additionally, these methods provide limited guidance for comprehensive spatial planning at the city center level. In summary, energy-based urban carbon emission accounting methods are widely used. However, they lack integration with spatial elements, limiting their support for spatial planning. In urban planning research, considerable effort has been devoted to improving the carbon accounting system for urban spatial elements. However, most studies are not consistent with central urban planning, leading to discrepancies in accounting and prediction results for resource-dependent cities and limited feedback on spatial changes. Therefore, developing carbon accounting and prediction methods aligned with urban planning boundaries and focused on urban spatial activity elements is crucial.

2. Method

2.1. Carbon accounting method based on space utilization activity data

Carbon accounting is a key method for assessing low-carbon urban development and monitoring the implementation of "dual carbon" targets in cities. It is primarily used for collecting foundational data during the early stages of urban planning and for monitoring and evaluation in later stages. Current urban carbon accounting research relies mainly on energy and economic activity data to calculate total carbon emissions within municipal boundaries. However, most urban carbon accounting methods cannot be directly linked to urban spatial planning data, making them difficult to apply in the planning process. To enhance the integration of urban spatial planning systems with carbon accounting methods, this study uses spatial activity metrics related to urban development as parameters to develop a carbon accounting framework integrated with urban spatial planning. To align with the existing carbon accounting system, this study adopts a production-based approach, covering direct emissions within urban boundaries and indirect emissions from energy activities like electricity distribution and regional heating. In constructing the accounting framework, this study uses the internationally recognized IPCC model, linking energy activities with spatial activities, which are then translated into urban spatial elements supporting energy consumption activities, as shown in Figure 1. Thus, by translating energy activities into spatial activities, the IPCC greenhouse gas inventory is connected to the urban spatial planning system, supporting the development of a carbon accounting method based on urban spatial elements.

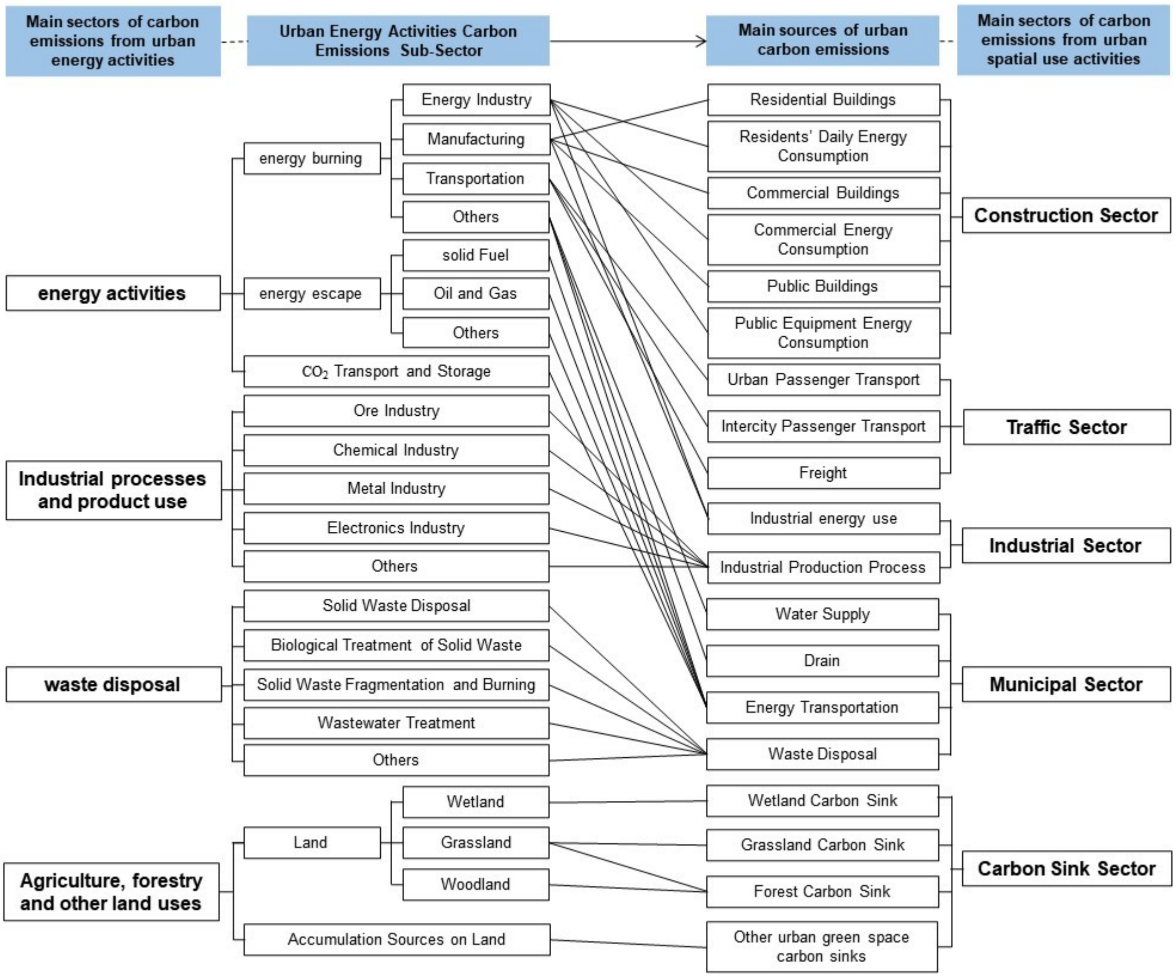

Figure 1. Carbon accounting framework for urban spatial elements. Source: Drawn by the author.

Based on the urban spatial element carbon accounting system, this study uses urban spatial activity data to account for carbon emissions from various sub-sectors and develops an accounting method for urban built-up areas focused on spatial activity data, as shown in Table 1. In this method, most basic urban spatial and activity data can be obtained from planning drawings, documents, or statistical yearbooks, while the annual average travel distance of private vehicles must be gathered from urban transportation survey reports or questionnaires. Compared to energy-based carbon accounting methods, this approach allows the process to be independent of energy data, instead using spatial activity data, making the results more timely. The results clearly reflect the impact of urban spatial development and changes in spatial activities on carbon emissions, thus supporting low-carbon urban spatial planning.

Table 1. Carbon accounting method based on space utilization activity data. Source: Created by the author.

Sectors	Urban spatial basic data	Space utilization activity data	Calculation method
Construction Sector	residential building area, commercial service facility land area, public management and public service land area, new building area	residential vacancy rate	$C_b^c = \left(S_{residence} \times r_{vacancy\,rate} \times k_{residence}^{tce} + \sum A_i \times k_i^{tce} + S_{new} \times k_{new}^{tce}\right) \times f_{tce}$
Industrial Sector	industrial and mining storage land area	average industrial output value	$C_i^c = A_m \times p_m \times k_m^{tce} \times f_{tce}$
Municipal Sector	heating building area, water supply pipeline length	population, per capita garbage collection volume, harmless garbage treatment rate, per capita sewage discharge	$C_m^c = L_{water} \times j_{water}^{electricity} \times f_{electricity} + (P \times \mu_{waste} \times r_{harmless} \times k_{waste}^{tce} + P \times \mu_{sewage} \times k_{sewage}^{tce} + S_{heating} \times j_{heating}^{tce}) \times f_{tce}$
Traffic Sector	average annual travel distance of private cars, total freight distance, and total passenger distance	number of private cars, electrification rate of residents' travel, total freight volume, total passenger trips	$C_t^c = L_{private\,car} \times C_{private\,car} \times r_{electrical} \times j_{new\,energy}^{electricity} \times f_{electricity} + L_{private\,car} \times C_{private\,car} \times (1 - r_{electrical}) \times j_{fuel}^{tce} \times f_{tce} + \sum L_i \times T_i \times k_{turnover}^{tce} \times f_{tce}$
Carbon Sink Sector	woodland, grassland, wetland, urban green space area, water area	—	$C_s^c = \sum A_i \times c_i$

2.2. Urban carbon emission prediction model

Based on the carbon accounting method focused on urban spatial elements, this study introduces an LSTM model to develop a prediction method for carbon accounting using urban spatial elements, as shown in Figure 2. The model is initially trained on 15 years of urban carbon emission data. The process involves repeated iterations of "model building—model training" to establish the carbon emission prediction model. The final prediction is made by predicting the fourth year's carbon emissions based on data from the preceding three years. Based on this, the model incorporates urban spatial element data to improve prediction accuracy. Key data include population, built-up area, industrial area, transport turnover, water supply pipe length, heating area, residential area, public facilities land, and urban green space. Since this model is based on a spatial element-oriented carbon accounting method, incorporating spatial data highly correlated with carbon emissions helps correct outliers, making predictions more accurate and consistent with urban development patterns.

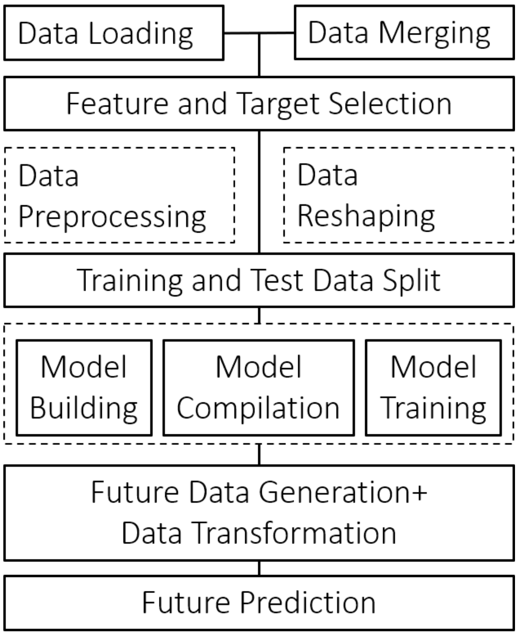

Figure 2. LSTM prediction model framework. Source: Drawn by the author.

3. Case study

3.1. Overview of the case study city

The study selects Harbin, a city in Heilongjiang Province, as the case study, collecting and organizing its energy and spatial activity data. Harbin, located in the southern part of Heilongjiang Province, China, has a temperate continental monsoon climate, with an average annual temperature of 5.2℃, long severe winters, and short cool summers. Consequently, residential energy consumption is lower in summer and higher in winter. Using statistical yearbook and remote sensing data, this study extracted Harbin's built-up area from 2017 to 2021 and identified changes, as shown in Figure 3, which presents the built-up area boundaries for representative years. The built-up area has expanded annually, with the six districts in the central urban area consistently showing expansion, particularly in the southern and northern regions. In the three peripheral districts, towns in the southwest and southeast initially contracted and then grew.

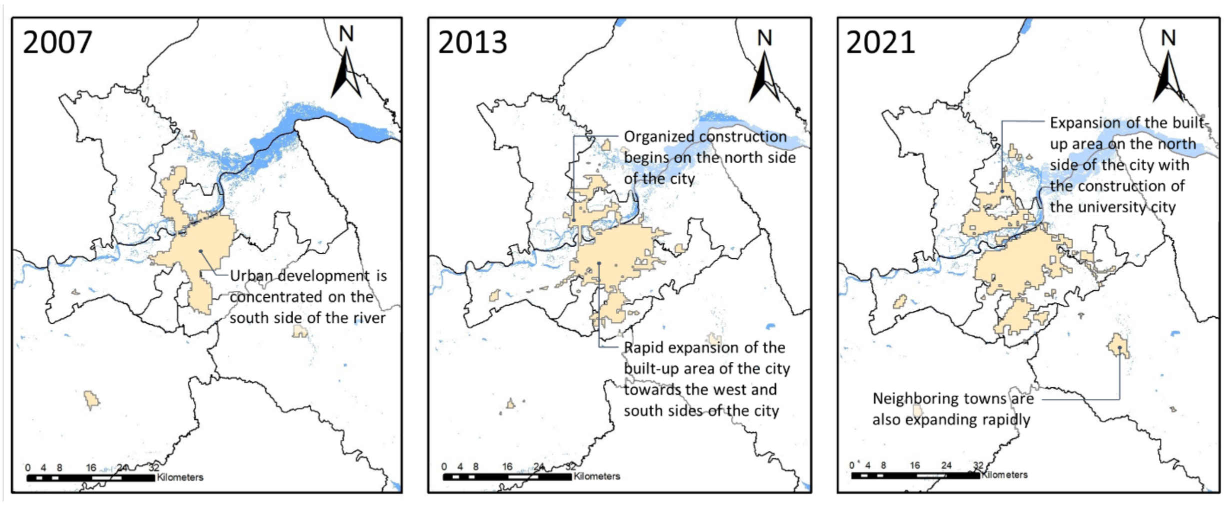

Figure 3. Spatial Changes in the Built-up Area of Harbin. Source: Drawn by the author.

3.2. Urban carbon emission accounting results

Using the spatial activity carbon accounting method, the study reviewed statistical yearbooks and transportation survey reports to obtain Harbin's spatial and activity data and conducted accounting of total and sectoral carbon emissions in the built-up area. The results were compared with those from energy-based carbon accounting, as shown in Figure 4. Overall, the accounting results were similar to those based on energy data. The building sector exhibited a similar trend over time, though with some differences in values. In the transportation sector, significant differences were observed between 2012 and 2017, mainly because data on private vehicle travel could only be estimated based on per capita travel expenditures from statistical yearbooks and questionnaires, resulting in larger errors. For other years, urban transportation survey data were available, leading to smaller discrepancies in the results.

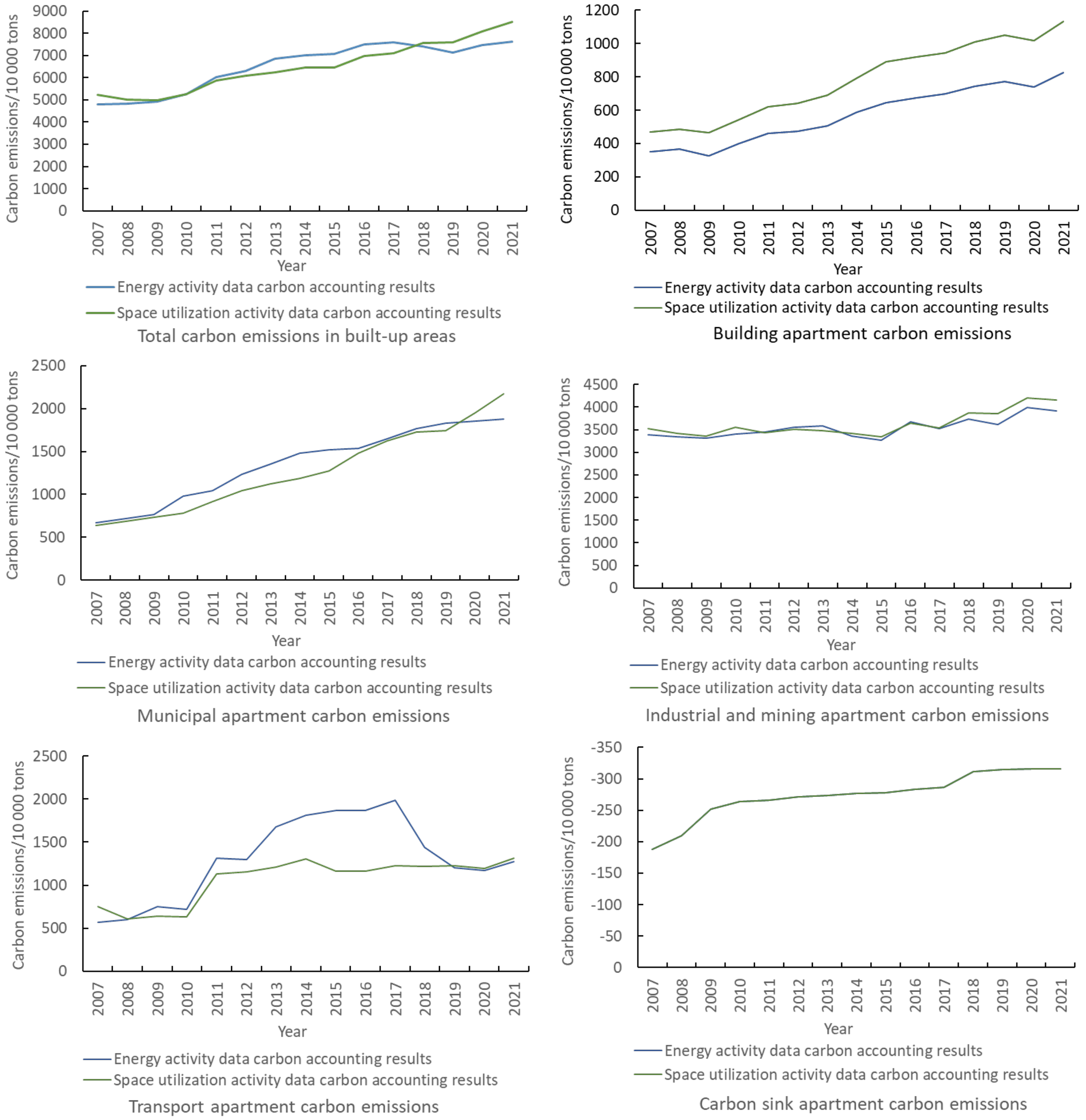

Figure 4. Comparison of carbon accounting results from both methods. Source: Drawn by the author.

Compared to the energy-based carbon accounting method, the spatial activity-based method accounts for carbon emissions within built-up areas based on urban spatial characteristics. In the building sector, the accuracy of results is significantly influenced by the vacancy rate and energy consumption per unit area; accurate data ensure that spatial activity-based accounting results closely match those of energy accounting. In the transportation sector, data on private vehicle travel significantly impact accounting precision. However, these data are rarely reported in statistical yearbooks and must be collected through transportation surveys or questionnaires, potentially introducing errors. In other sectors, relevant data can be obtained from statistical yearbooks and greenhouse gas inventories, leading to high accuracy in results. Overall, results from the spatial activity-based method are numerically similar to those from the energy-based method, while being easier to obtain and more widely applicable. Furthermore, due to its strong association with urban spatial elements, this method can adjust results in real time according to changes in the built-up area, reducing dependence on energy data and providing greater flexibility and scalability.

In summary, developing a carbon accounting method for urban built-up areas based on spatial activity data is a crucial tool to support dual carbon targets and assist urban spatial planning in establishing low-carbon cities.

3.3. Urban carbon emission prediction results

Using the carbon accounting results of the case study city, the study imported 15 years of Harbin's carbon emission data into the prediction model and obtained predictions based on a logic of predicting one year from every three years of data, as shown in Figure 5. The carbon emission forecast for 2023 to 2050 shows an initial increase in urban emissions followed by a decrease. Emissions are projected to peak around 2030 and then gradually decline. However, due to the limited initial sample size, the input data for the prediction model are relatively small and mainly consist of homogeneous carbon emission data, leading to some errors in predictions.

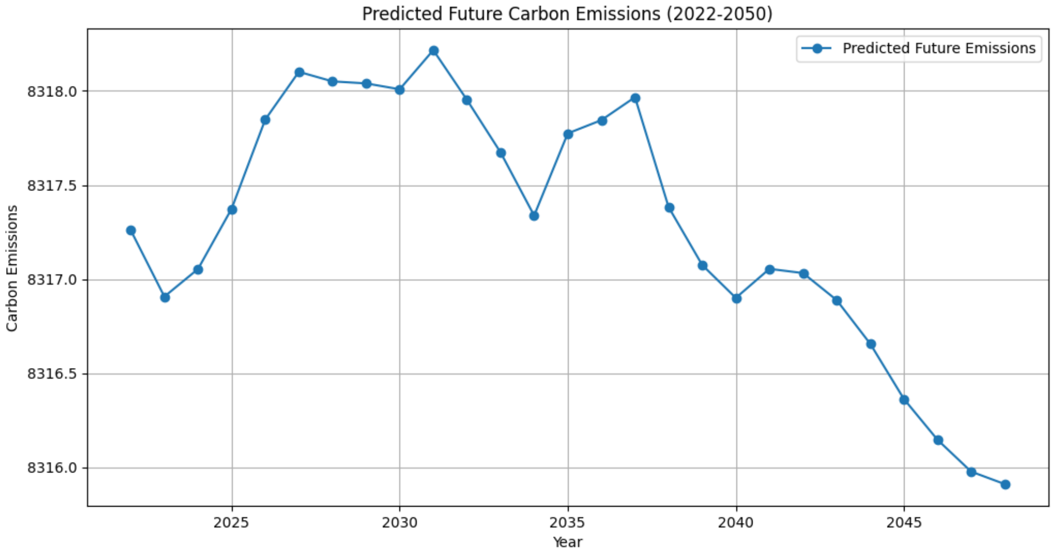

Figure 5. Urban carbon emission prediction results. Source: Drawn by the author.

To improve prediction accuracy, the study introduced a multi-scenario prediction technique. By defining multiple potential future urban development scenarios and inputting scenario-specific data into the prediction model, the volume of baseline sample data was increased, improving prediction accuracy. In this process, three future development scenarios were defined: the Baseline Scenario, Low-Carbon Scenario, and High-Carbon Scenario, with their main characteristics shown in Figure 6. The Baseline Scenario assumes no major changes in policies or technology, with urban development continuing along its current trajectory. The Low-Carbon Scenario assumes strong policy measures and rapid technological advancements, leading to a significant reduction in carbon intensity. The High-Carbon Scenario prioritizes urban growth over environmental concerns, resulting in increased carbon emissions.

Baseline Scenario

Basic Information:

- The Baseline Scenario assumes that future development trends will continue as they have in the past few years, with **no major policy changes or technological breakthroughs**.
- This is **a "business-as-usual" scenario**, assuming that economic and social development will proceed smoothly along the current trajectory.

Assumptions:

- Indicators such as **urban population growth, industrial development, and building area expansion** maintain the average growth rate of the past.
- The **city's energy structure, transportation modes, and carbon emission intensity** remain consistent with historical data.
- No new major policies are introduced; **environmental protection and carbon reduction measures** continue at current levels.

High-Carbon Scenario

Basic Information:

- Future urban development will **prioritize economic growth**.
- Economic and social development will **proceed smoothly along the current trajectory**.

Assumptions:

- **Faster urban expansion**, accelerated industrialization, and urbanization, with a rapid increase in building area and industrial land.
- The energy structure remains **dominated by fossil fuels**, with slow development of renewable energy and increased carbon intensity in transportation and buildings.
- **Weakening of environmental protection policies**, lacking carbon taxes and emission restrictions.

Low-Carbon Scenario

Basic Information:

- There will be **proactive policy interventions and technological innovations** in the future.
- This scenario reflects an optimal emission reduction path, with **strong policy measures, rapid social transformation, and a significant decline in carbon intensity**.

Assumptions:

- Promote **new energy technologies**, reduce dependence on fossil fuels, and increase the share of renewable energy in the energy mix.
- Implement stricter urban planning and energy-saving policies to **reduce energy consumption in buildings and carbon emissions from transportation**.

Figure 6. Details of urban development scenarios. Source: Drawn by the author.

By introducing the multi-scenario prediction technique, the study incorporated three potential urban development scenarios into the model, resulting in carbon emission forecasts for each scenario, as shown in Figure 7. According to the results, if urban development is left unchecked, carbon emissions will fluctuate but overall levels will remain relatively stable. If urban development focuses only on economic growth and expansion and ignores sustainability, carbon emissions could increase rapidly. Conversely, if urban development prioritizes low-carbon and sustainability goals, carbon emissions will gradually decline.

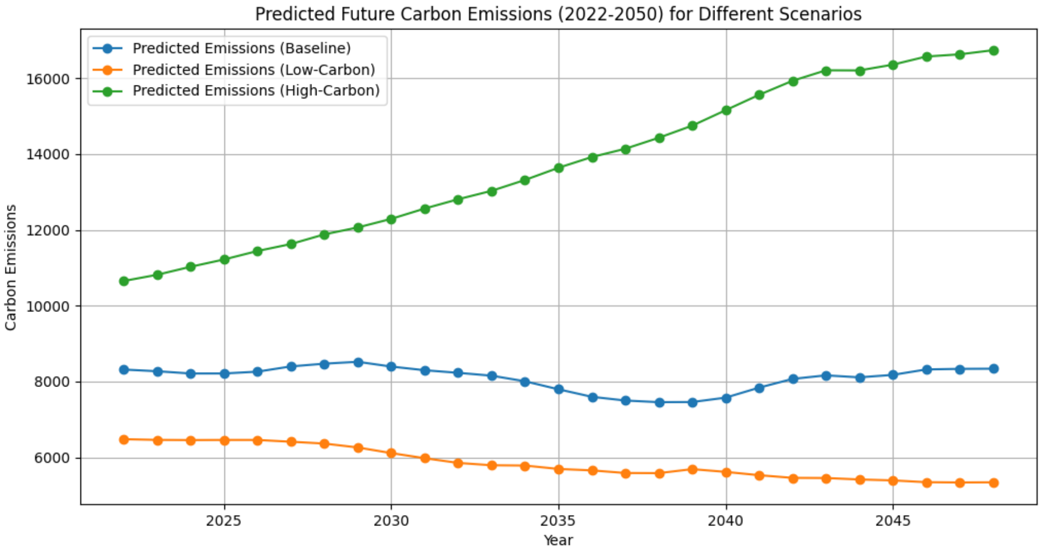

Figure 7. **Multi-Scenario carbon emission prediction results.** Source: Drawn by the author.

4. Conclusions

The study shows that the carbon accounting method based on urban spatial elements can accurately and efficiently assess carbon emissions, providing valuable guidance for the development of targeted low-carbon city optimization strategies. The introduction of carbon emission prediction modeling further enhances the ability to predict future urban emissions, helping policy makers to formulate effective strategies for sustainable urban development. In addition, the multi-scenario simulation reveals the significant impact of different spatial planning approaches on urban carbon emissions, providing important insights for improving the sustainability of urban development planning. To better illustrate the effects of changes in urban spatial elements on carbon emissions, this study explores the effects of multiple factors through regression analysis, as shown in Figure 8. On the left side of the figure are positive influencing factors, the increase of which leads to an increase in carbon emissions; on the right side are negative influencing factors, the increase of which reduces carbon emissions, indicating a positive effect on the environment. By further analyzing the spatial elements, the impact of spatial changes on carbon emissions can be assessed, so that more targeted spatial renewal strategies can be developed in urban planning. By inhibiting the growth of positive factors and promoting the development of negative factors, the construction of low-carbon cities can be effectively promoted and sustainable urban development can be realized.

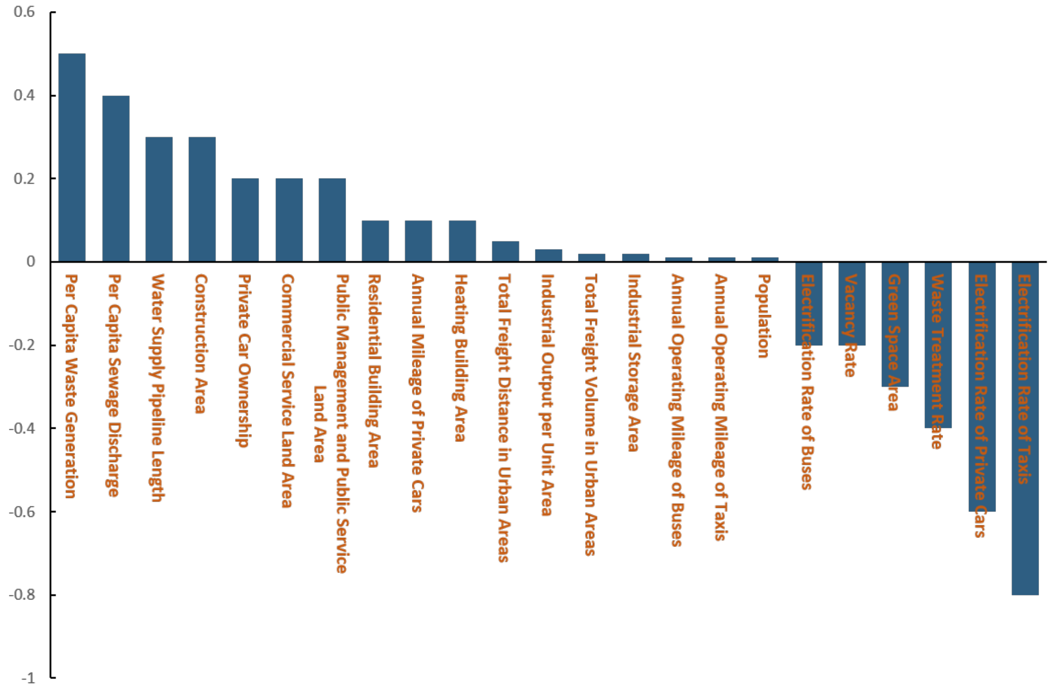

Figure 8. **Impact of urban spatial elements on carbon emissions.** Source: Drawn by the author.

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