Research on Carbon Accounting Methods for Urban Areas Based on Spatial Data Utilization

Abstract: As climate change becomes a significant global threat, the pursuit of carbon peak and carbon neutrality is now essential for urban development in China. Carbon accounting is a crucial technical tool for monitoring urban carbon emissions and guiding low-carbon urban construction. This study, which focuses on urban built-up areas, integrates carbon accounting methods with urban spatial elements, significantly aiding the achievement of 'dual carbon' development goals in cities. Using Harbin City, Heilongjiang Province as a case study, this paper summarizes and analyzes fifteen years of data on energy and spatial usage to develop a carbon accounting system for urban built-up areas. Additionally, it formulates a carbon accounting method for urban built-up areas based on spatial usage, and validates its accuracy by comparing the results with those from energy usage carbon accounting. Based on these findings, the study proposes pathways for predicting urban carbon neutrality and specialized assessments for low-carbon construction, thus supporting the 'carbon neutrality' goals in national spatial planning.

Keywords: Carbon Neutrality Goals; Built-Up Area; Spatial Usage Activity Data; Carbon Accounting; Application Pathways

1. Introduction

To address global climate change risks, China announced at the 75th United Nations General Assembly its commitment to reach carbon peak by 2030 and achieve carbon neutrality by 2060. Cities, as hubs of human activity, are major contributors to high energy consumption and carbon emissions, accounting for over 80% of global greenhouse gas emissions (Lynn and Peeva, 2021a, Dhakal, 2009a). Research indicates that strategically arranging and coordinating urban spaces effectively reduces regional carbon emissions (Li *et al.*, 2022a, Newman and Kenworthy, 1998). Therefore, developing a low-carbon, sustainable urban strategy is crucial for achieving carbon neutrality goals.

With the complete implementation of national land and spatial planning, supporting carbon neutrality goals and fostering urban low-carbon development have become key objectives in urban construction (Xiong *et al.*, 2021b, Zheng *et al.*, 2022b). Currently, urban carbon accounting methods are crucial technical tools in low-carbon urban planning research (Ye, 2009b, Zheng *et al.*, 2021c, Chen *et al.*, 2022c). However, current carbon accounting methods face challenges such as poor integration with spatial elements, and their scope often misaligns with the national land and spatial master plans at the central city level. To enhance the role of urban carbon accounting in supporting land and spatial planning, this study develops a built-up area carbon accounting system based on space use activities, following the "accounting system - benchmark formulation - method construction - result verification" framework. Harbin City is used as a case study to validate the method's accuracy. Building on this, the study proposes an application pathway for this carbon accounting method in territorial spatial planning.

Currently, urban carbon accounting is categorized into production-based methods (PBA), which utilize energy use data, and consumption-based methods (CBA), which rely on economic input and output data (Peters, 2008, Guan *et al.*, Wiedmann, 2009c). The "IPCC National Greenhouse Gas Inventory" is a production-based carbon accounting model developed by the Intergovernmental Panel on Climate Change, established by the World Meteorological Organization and the United Nations Environment Program. It is an important tool for countries and cities around the world to establish greenhouse gas emissions. The more authoritative approach to the inventory process (Chen, 2011). This method categorizes regional carbon emissions into four sectors: energy activities, industrial processes, agriculture and forestry, and waste disposal. Energy activity data is used to calculate the carbon emissions of each sector and summarize them step by step, and finally calculates regional greenhouses. Gas emissions. Its global use in climate monitoring has led many cities and regions to adopt this model for calculating urban carbon emissions and compiling greenhouse gas inventories. Urban policymakers and researchers can use these accounting results to assess the impacts of energy use changes on carbon emissions and monitor shifts in the city's emission structure. Therefore, this method has become the most commonly used urban carbon accounting technology in the field of urban planning (Steininger *et al.*, 2014a, Lin and Sun, 2010, Chen *et al.*). Despite its advantages, the integration of energy-based carbon accounting with urban spatial elements is poor, negatively affecting urban planning due to low correlation between results and spatial factors. Insufficient feedback, interaction and support (Zheng *et al.*, 2021c, Xu *et al.*, 2022d, Chen *et al.*, 2022c).

Enhancing the correlation between carbon accounting results and urban spatial elements has emerged as a crucial research direction (Su *et al.*, 2014b). Scholars have utilized nighttime light data to analyze the temporal evolution and spatial distribution of urban carbon emissions, initially establishing a coupling relationship with urban spatial elements (Meng *et al.*, 2017, Shi *et al.*, 2016, Lv *et al.*, 2020, Ao *et al.*, 2022e). In-depth research into the emission reduction mechanisms of urban and rural spatial development has led to the establishment of a "land use-carbon emission" correlation framework, based on classifications, inventory divisions, and emission reduction paths. This approach has been applied in cities like Beijing and Shanghai, with urban elements as core components of the carbon accounting method (Jiang *et al.*, 2013a, Ju, 2013b, Li and Ren, 2019). Currently, the urban spatial elements used in research are relatively simple, primarily involving data on land use scales and average activity levels, with some key activity data being difficult to obtain. Scholars have proposed a universal carbon accounting method for urban spaces that uses the national greenhouse gas inventory framework to integrate energy consumption data with urban land use, establishing a research framework focused on industry, construction, transportation, and carbon sinks (Wang and He, 2015, Xu *et al.*, 2022d). Building on this, scholars have developed a carbon assessment framework for municipal master plans that incorporates all natural resource elements, using Wuhan as a case study for validation (Luo *et al.*, 2023). Currently, there has been progress in developing carbon accounting methods for urban spaces, although these methods typically focus on entire cities and account for all urban space elements' carbon emissions. This approach is particularly effective in urban areas characterized by extensive construction and high development intensity. However, this method often yields inaccurate results for cities dependent on agriculture and mineral resources, failing to accurately reflect their development and construction levels. Additionally, this method provides limited guidance for comprehensive land and spatial planning at the central urban level.

In summary, the prevalent method of urban carbon accounting based on energy data is widely utilized. However, its integration with spatial elements is inadequate, and its results provide limited support for spatial planning. In urban planning, considerable research has focused on refining carbon accounting systems for urban spatial elements. Yet, the scope of most studies does not align with central city planning, leading to significant discrepancies in the accounting results for resource-dependent cities and limited feedback on spatial changes in urban areas. Consequently, it is crucial to develop an urban carbon accounting method that aligns with municipal planning scopes and focuses on urban spatial activity elements.

2. Methodology

2.1 Establishing a carbon accounting system for urban built-up areas

To improve compatibility and support between urban carbon accounting results and central urban master planning, a universal carbon accounting method for urban built-up areas needs to be established. During this process, a carbon accounting system tailored for urban built-up areas should be established, utilizing energy activity data to calculate their carbon emissions. This establishes benchmark data and lays the groundwork for the methods detailed in subsequent sections. This system will also set standards to validate the results.

The "IPCC National Greenhouse Gas Inventory" is the principal method for preparing greenhouse gas emission inventories globally, recognized for its high authority and scientific rigor. As a method for carbon emission accounting across municipalities and larger regions, this approach provides a comprehensive and generalized division of accounting categories. However, within the smaller scope of urban built-up areas, this method includes carbon emissions from non-built-up sectors like agriculture and forestry in the energy and waste treatment calculations, complicating data acquisition. This study adapts the carbon accounting framework from the "IPCC National Greenhouse Gas Inventory". It reclassifies carbon emission categories to suit the specific characteristics and research requirements of urban built-up areas, as shown in Figure 1. The changes in accounting scope mean that the carbon accounting system for urban built-up areas differs from the IPCC guidelines. Specifically, carbon emissions from electricity in urban built-up areas are allocated to the electricity use processes across different sectors. To prevent double counting, it excludes carbon emissions from electricity production in industrial and mining sectors. Additionally, as urban built-up areas exclude agricultural land, agricultural carbon emissions are omitted from the accounting. This adaptation links the urban built-up area carbon accounting system with the "IPCC National Greenhouse Gas Inventory", setting the stage for further development of carbon accounting methods.

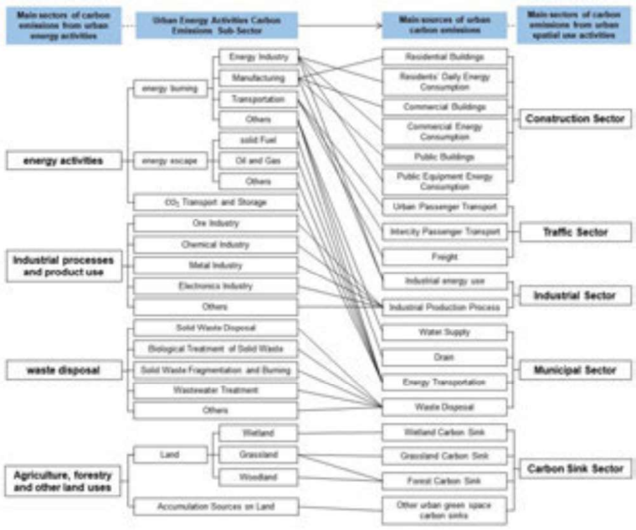

Figure 1 Carbon accounting system for urban built-up areas

2.2 Developing benchmark data for carbon accounting in urban built-up areas based on energy activity data

To establish accurate benchmark data for verifying carbon emissions in urban built-up areas, detailed calculations for each emission category should be performed using the most commonly used energy activity data. Changes in accounting entities necessitate adjustments to the specific accounting processes. Consequently, this study employs the IPCC model within the urban built-up area accounting system to calculate carbon emissions across various sectors, thereby developing an energy data-oriented carbon accounting method for urban built-up areas, as detailed in Table 1. Using this method, energy activity data for urban built-up areas is sourced from resources like the Urban Statistical Yearbook and the Urban Energy Statistical Yearbook. Furthermore, using energy conversion tables, challenging-to-calculate energy data (like raw coal, coke, gasoline, diesel) are converted into standard coal equivalents. Building on this, carbon emission coefficients for electricity, standard coal, and other energies are derived from provincial and national greenhouse gas inventory guidelines, leading to the development of a carbon accounting method tailored for urban built-up areas.

Table 1 Carbon accounting method for urban built-up areas based on energy activity data

Sectors	City Energy Activity Data	Data Related to Carbon Emission Calculations	Data Sources	Calculation Method
Construction Sector	residential electricity consumption of urban residents, electricity consumption in commercial and service industries, gas consumption in residential and service industries, energy consumption in the construction process of new buildings, and energy consumption in maintenance of old buildings	electricity carbon emission coefficient, natural gas carbon emission coefficient, liquefied petroleum gas carbon emission coefficient, unit standard coal energy consumption carbon emission coefficient	City Statistical Yearbook, City Energy Statistical Yearbook, Provincial Greenhouse Gas Inventory Preparation Guide, National Greenhouse Gas Inventory Guide	$C_b^c = \sum E_{electricity}^i \times f_{electricity} + \sum E_{gas}^i \times k_{gas}^{tce} \times f_{tce} + \sum E_{LPG}^i \times k_{LPG}^{tce} \times f_{tce} + \left(E_{tce}^{construction} + E_{tce}^{maintenance}\right) \times f_{tce}$
Industrial and Mining Sector	in addition to electricity production, energy used in industrial production (including raw coal, coke, natural gas, gasoline, crude oil, kerosene, diesel, and electricity)	standard coal conversion coefficient for various types of energy and carbon emission coefficient of energy consumption per unit of standard coal	City Energy Statistical Yearbook, Standard Coal Conversion Reference Coefficient Table for Various Energy Resources, National Greenhouse Gas Inventory Guide	$C_i^c = \sum E_i^{industry} \times k_i^{tce} \times f_{tce}$

Municipal Sector	public utility electricity consumption, domestic waste treatment capacity, domestic sewage treatment capacity, heating steam heat, heating hot water heat	electricity carbon emission coefficient, unit waste treatment electricity consumption, unit sewage treatment electricity consumption, thermal energy conversion coefficient to standard coal, unit standard coal energy consumption carbon emission coefficient	City Statistical Yearbook, City Energy Statistical Yearbook, Various Energy Standard Coal Conversion Reference Coefficients Table, Provincial Greenhouse Gas Inventory Preparation Guide, National Greenhouse Gas Inventory Guide	$C_m^c = E_{electricity}^{public\ utilities} \times f_{electricity} + (V_{waste} \times k_{waste}^{electricity} + V_{sewage} \times k_{sewage}^{electricity}) \times f_{electricity} + (V_{steam}^{central\ heating} + V_{hot\ water}^{central\ heating}) \times k_{heat}^{tce} \times f_{tce}$
Traffic Sector	transportation electricity consumption, transportation gasoline amount, transportation diesel amount, transportation kerosene amount, transportation natural gas amount	standard coal conversion coefficient for various types of energy and carbon emission coefficient of energy consumption per unit of standard coal	City Statistical Yearbook, City Energy Statistical Yearbook, Various Energy Standard Coal Conversion Reference Coefficients Table, Provincial Greenhouse Gas Inventory Preparation Guide, National Greenhouse Gas Inventory Guide	$C_t^c = \sum E_i^{traffic} \times k_i^{tce} \times f_{tce}$
Carbon Sink Sector	woodland, grassland, wetland, urban green space area, water area	carbon sequestration coefficients of woodlands, grasslands, wetlands, urban green spaces, and water bodies	City Statistical Yearbook, Provincial Greenhouse Gas Inventory Compilation Guide	$C_s^c = \sum A_i \times c_i$

C_b^c is the building sector's carbon emissions; $E_{electricity}^i$ is electricity consumption of class i buildings, i is various urban land building types, including residential buildings, commercial buildings, and public service buildings; $f_{electricity}$ is the carbon emission coefficient per unit of electricity use; E_{gas}^i is the amount of natural gas used in class i buildings; k_{gas}^{tce} is the unit natural gas conversion standard coal coefficient; f_{tce} is the carbon emission coefficient per unit of standard coal; E_{LPG}^i is the amount of liquefied petroleum gas used in type i buildings; k_{LPG}^{tce} is the liquefied petroleum gas conversion coefficient to standard coal; $E_{tce}^{construction}$ is the standard coal usage converted from energy in the construction process of new buildings; $E_{tce}^{maintenance}$ is the energy–converted standard coal usage in the maintenance process of old buildings; C_i^c is the carbon emissions of the industrial and mining sector; $E_i^{industry}$ is the energy usage of category i in industrial production processes above regulations except for electricity production. i represents various energy types, including raw coal, coke, natural gas, gasoline, crude oil, kerosene, diesel, electricity, etc.; k_i^{tce} is the standard coal conversion coefficient of type i energy; C_m^c is the carbon emissions of the municipal sector; $E_{electricity}^{public\ utilities}$ is the electricity consumption of public utilities; V_{waste} is the amount of solid waste discharge; $k_{waste}^{electricity}$ is the electricity consumption per unit of solid waste treatment; V_{sewage} is the amount of sewage discharge; $k_{sewage}^{electricity}$ is the electricity consumption per unit of sewage treatment; $V_{steam}^{central\ heating}$ is the central heating steam usage; $V_{hot\ water}^{central\ heating}$ is the usage of central heating hot water; k_{heat}^{tce} is the coefficient of conversion of unit thermal value to standard coal; C_t^c is the carbon emissions of the transportation sector; $E_i^{traffic}$ is the energy usage of category i in the transportation sector, where i represents each energy type, including raw natural gas, gasoline, kerosene, diesel, electricity, etc.; C_s^c is the carbon absorption amount of the carbon sink department; A_i is the area of type i land, and i represents various types of land that can provide carbon sinks, including woodland, grassland, wetland, urban green space, and water area; c_i is the carbon sink coefficient of various land uses;

2.3 Establishing an urban built-up area accounting method oriented to space use activity data

To strengthen the integration of carbon accounting methods with urban spatial elements, we investigated how to extract human activity and space use data within urban built-up areas. Using the urban built-up area carbon accounting framework that relies on energy data, we replaced energy use data in each department with space use activity data, establishing a new carbon accounting method centered on urban spatial elements.

Using the urban built-up area carbon accounting system, this study calculates carbon emissions for each sub-sector using urban space use activity data, and develops a spatial activity data-oriented accounting method, as detailed in Table 2. In this method, basic urban space and space use activity data are sourced from planning documents, texts, and statistical yearbooks, while data on the average annual travel distance of private cars is derived from urban traffic surveys or questionnaires. This provides a method to obtain necessary data. Compared to energy data-based methods, this approach reduces reliance on energy data for carbon accounting in urban built-up areas, utilizing spatial activity data to produce more timely results. Additionally, the results clearly illustrate the impact of changes in urban spatial development and activities on carbon emissions, supporting low-carbon urban spatial planning.

Table 2 Carbon accounting method for urban built-up areas based on space utilization activity data

Sectors	Urban spatial basic data	Space utilization activity data	Data related to carbon emission calculations	Data sources	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	residential energy consumption coefficient per unit building area, energy consumption coefficient for commercial and service facilities per unit land area, energy consumption coefficient during	provincial energy statistical yearbook, city statistical yearbook, standard coal conversion reference coefficient table for various energy sources,	$C_b^c = \left(S_{residence} \times r_{vacancy\ rate} \times k_{residence}^{tce} + \sum A_i \times k_i^{tce} + S_{new} \times k_{new}^{tce}\right) \times f_{tce}$

			construction process per unit building area, and carbon emission coefficient for energy consumption per unit standard coal	national greenhouse gas inventory guide	
Industrial and Mining Sector	industrial and mining storage land area	average industrial output value	energy consumption per unit of industrial GDP, carbon emission coefficient of energy consumption per unit of standard coal	Provincial Energy Statistical Yearbook, City Statistical Yearbook, National Greenhouse Gas Inventory Guide	$C_i^c = A_m \times p_m \times k_m^{tce} \times f_{tce}$
Municipal Sector	heating building area, water supply pipeline length	population, per capita garbage collection volume, harmless garbage treatment rate, per capita sewage discharge	energy consumption per unit of garbage removal, energy consumption per unit sewage treatment, electricity consumption per unit length of pipeline water transportation, energy consumption per unit heating area, carbon emission coefficient of unit standard coal energy consumption, electricity carbon emission coefficient	Provincial Energy Statistical Yearbook, City Statistical Yearbook, City Energy Statistical Yearbook, Provincial Greenhouse Gas Inventory Preparation Guide, National Greenhouse Gas Inventory Guide	$C_m^c = L_{water} \times j_{water}^{electricity} \times f_{electricity} + \left(P \times \mu_{waste} \times r_{harmless} \times k_{waste}^{tce} + P \times \mu_{sewage} \times k_{sewage}^{tce} + S_{heating} \times j_{heating}^{tce}\right) \times f_{tce}$

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	energy consumption per unit turnover, electricity consumption per unit travel distance, electricity consumption per unit travel distance of new energy vehicles, energy consumption of fuel vehicles per unit travel distance	Urban Traffic Survey Report, Urban Statistical Yearbook, Urban Energy Statistical Yearbook, Provincial Greenhouse Gas Inventory Preparation Guide, National Greenhouse Gas Inventory Guide	$C_t^c = L_{private\ car} \times C_{private\ car} \times r_{electrical} \times j_{new\ energy}^{electricity} \times f_{electricity} + L_{private\ car} \times C_{private\ car} \times (1 - r_{electrical}) \times j_{fuel}^{tce} \times f_{tce} + \sum L_i \times T_i \times k_{turnover}^{tce} \times f_{tce}$
Carbon Sink Sector	woodland, grassland, wetland, urban green space area, water area	—	carbon sequestration coefficients of woodlands, grasslands, wetlands, urban green spaces, and water bodies	City Statistical Yearbook, Provincial Greenhouse Gas Inventory Compilation Guide	$C_s^c = \sum A_i \times c_i$

C_b^c is the carbon emissions of the construction sector; $S_{residence}$ is the residential building area; $r_{vacancy\ rate}$ is the residential vacancy rate; $k_{residence}^{tce}$ is the energy consumption per unit residential building area (converted in standard coal); A_i is the area of type i urban land, including land for commercial service industry facilities, public management and public services; k_i^{tce} is the energy consumption per unit area of type i land (converted in standard coal); S_{new} is the new building area; k_{new}^{tce} is the energy consumption per unit of new building area (converted in standard coal); f_{tce} is the carbon emission coefficient per unit of standard coal; C_i^c is the carbon emissions of the industrial and mining sector; A_m is the area of industrial and mining land; p_m is the average industrial output value; k_m^{tce} is the energy consumption per unit of industrial GDP; C_m^c is the carbon emissions of the municipal department; L_{water} is the length of the water supply pipeline; $j_{water}^{electricity}$ is the electricity consumption per unit water supply distance; $f_{electricity}$ is the carbon emission coefficient per unit electricity consumption; P is the population; μ_{waste} is the average garbage removal volume; $r_{harmless}$ is the harmless garbage chemical treatment rate; $k_{waste}^{electricity}$ is the energy consumption for harmless treatment of garbage; μ_{sewage} is the per capita sewage discharge; k_{sewage}^{tce} is the unit sewage treatment energy consumption; $S_{heating}$ is the central heating building area; $j_{heating}^{tce}$ is the energy consumption per unit heating area; C_t^c is the carbon emissions of the transportation sector; $L_{private\ car}$ is the average annual driving distance of private cars; $C_{private\ car}$ is the number of private cars; $r_{electrical}$ is the electrification rate of private cars; $j_{new\ energy}^{electricity}$ is the electricity consumption of new energy vehicles per unit travel distance; $f_{electricity}$ is the unit electricity consumption carbon emission coefficient; j_{fuel}^{tce} is the energy consumption of fuel vehicles per unit travel distance (converted to standard coal); L_i is the transportation distance of type i, i represents the type of transportation, including passenger transportation and freight; T_i is the transportation volume of type i, among them, freight is the freight volume, and passenger transportation is the converted passenger volume; $k_{turnover}^{tce}$ is the unit turnover energy consumption; C_s^c is the carbon absorption amount of the carbon sink department; A_i is the I type land area, and i represents the various types of land that can be provided the types of land used for carbon sinks include woodland, grassland, wetland, urban green space, and water bodies; c_i is the carbon sink coefficient of various land uses;

3. Case study

Based on the carbon accounting method described earlier, this study calculates carbon emissions for various sectors in Harbin's built-up areas from 2007 to 2021 using energy activity data, establishing this as benchmark data (see Figure 2). The accounting results indicate that total carbon emissions in Harbin's built-up areas have generally increased. Specifically, the industrial and mining sector, which contributes over 50% of the emissions, displays a fluctuating but overall upward trend. However, as urban development and industrial transformation progress, its share of total emissions has gradually declined. In contrast, the transportation sector is the only one showing a downward trend in emissions. This decline is attributed to the growing electrification of transportation, leading to a decrease in gasoline and diesel use and an increase in electricity consumption each year. Due to the lower carbon emission coefficient of electricity compared to other fossil fuels, emissions from this source are decreasing. The carbon accounting results from energy data clearly illustrate changes in emissions within the urban built-up area and accurately analyze the impact of energy use changes on these emissions. These results have gained broad recognition in the academic community. Using these calculation results as benchmark data provides solid support for verifying accuracy in subsequent analyses.

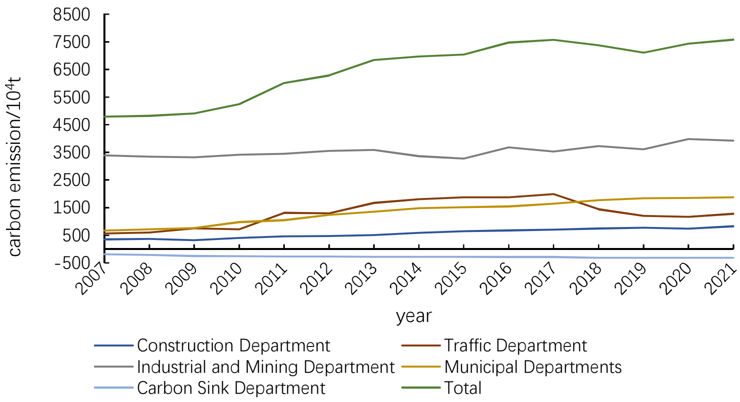

Figure 2 Harbin built-up area carbon accounting benchmark data for energy activity data

Utilizing the space use activity carbon accounting method, we analyzed statistical yearbooks and traffic survey reports to gather basic spatial and activity data for Harbin. We then calculated total and departmental carbon emissions in built-up areas. These results were compared with those from energy use activities, as detailed in Figure 3. The overall accounting results closely align with those derived from energy data. Specifically, the construction sector shows similar trends in both sets of data, though there are some differences in the values. The transportation department's accounting results from 2012 to 2017 show significant differences, primarily due to estimations based on per capita travel expenditure and survey data, leading to substantial discrepancies. For other years, data from urban traffic surveys provide more accurate results, resulting in minimal discrepancies in the accounting.

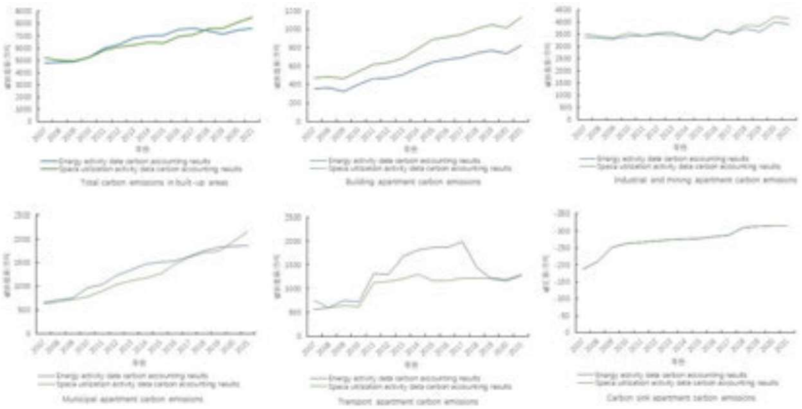

Figure 3 Comparison chart of dual method calculation results

To scientifically validate the accuracy of the carbon accounting method for space activities, we employed regression analysis to compare the results of space use activities with those from energy activities. The findings are presented in Figure 4 and Table 3. The verification indicates a high correlation of 99.2% between the two methods, with a standard error of 256.7, suggesting significant model reliability. These results confirm the high accuracy of the carbon accounting for space use activities, with minimal discrepancies compared to energy use results, demonstrating practical application value.

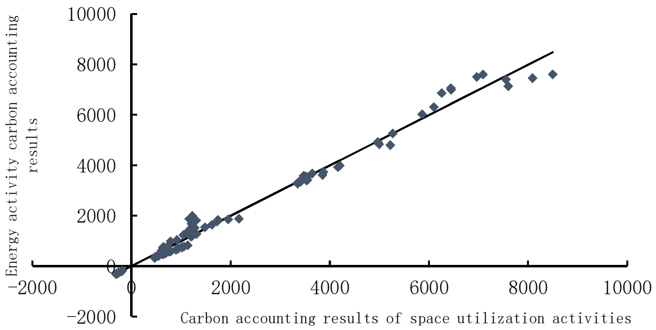

Figure 4 Dual method accuracy verification results

Table 3 Regression model statistics table

R	R^2	Adjusted R^2	Standard Deviation	Significance
.996	.992	.992	256.697	0.000

Unlike the energy-based method, the carbon accounting method for space use activities calculates emissions within built-up areas based on the city's spatial characteristics. In particular, the construction sector's results are heavily influenced by the accuracy of data on building vacancy rates and energy consumption per unit area. Accurate statistics ensure that carbon accounting for space use activities aligns closely with energy-based results. In the transportation sector, the accuracy of private car travel data significantly influences accounting results. However, statistical yearbooks rarely contain official data on this. This data must be compiled from urban traffic surveys or questionnaires, potentially introducing errors. For other sectors, data from statistical yearbooks and greenhouse gas inventories ensure highly accurate accounting results. Overall, the results from the space use activity method are numerically close to those from energy methods, with simpler data acquisition and broad applicability. Additionally, this method's close link to urban spatial elements allows for real-time adjustments to the accounting results based on spatial changes, enhancing its flexibility and scalability. In summary, developing a carbon accounting method based on space usage activity data is crucial for achieving dual carbon goals and supporting the creation of low-carbon cities through land spatial planning.

4. application path

As the carbon accounting method for urban built-up areas, based on space use activity data, is refined, it can be integrated into the preparation, monitoring, and evaluation phases of the central city's national land and space master plan. During the planning phase, this method can predict the carbon reduction potential of development plans and support decision-making in building low-carbon cities. In the monitoring and evaluation phase, this method enables the establishment of low-carbon city evaluation indicators, facilitating the use of scientific and technological approaches to assess low-carbon city development.

Urban carbon emission prediction is a crucial technical tool for guiding low-carbon city construction and forecasting urban development trajectories. Current methods generally use data on urban population, energy consumption, and economic growth to simulate and forecast city-wide carbon emission changes. However, these data can be difficult to acquire, often show weak correlation with urban spatial elements, and do not allow for periodic adjustments based on urban development. As carbon accounting for urban built-up areas expands to include spatial usage data, a time series prediction model using neural networks can be developed to estimate emissions more precisely. This model integrates closely with spatial usage activities in urban built-up areas, enhancing its relevance and accuracy. It enables real-time predictions of carbon emissions based on changes in land use and urban spatial planning, clearly demonstrating the impact of these strategies on carbon reduction. Additionally, the model incorporates multi-scenario simulation and prediction to evaluate different urban development scenarios—baseline, low-carbon, and high-carbon—and to establish respective carbon emission forecasts for various urban spatial strategies.

To ensure steady progress in low-carbon city development and the achievement of dual-carbon goals, my country has initiated several low-carbon city pilot projects and continuously evaluates their progress. A key tool in this effort is the special assessment of low-carbon city construction, which supports planning decisions and ensures the implementation of carbon reduction strategies. Within the carbon accounting framework for urban built-up areas based on space use data, the LMDI decomposition method measures the contribution and sensitivity of each element by analyzing changes in their carbon emission impacts. The contribution reflects the influence of various factors on the rates and amounts of carbon emissions and absorption, while sensitivity indicates the efficiency and effectiveness of these factors in reducing emissions and enhancing carbon sinks (Luo *et al.*, 2023). By identifying key factors, we can pinpoint the most impactful elements of space use activities on urban carbon emissions and develop a specialized evaluation index system for low-carbon cities based on carbon accounting. The introduction of this indicator system offers quantitative standards for monitoring and evaluating urban planning, and provides technical support for optimizing low-carbon urban spatial resources.

5. Conclusion

Currently, China's strategies for achieving carbon peak and carbon neutrality have introduced new requirements and visions for urban planning. Developing carbon accounting technology that integrates urban spatial elements and aligns with central urban areas' master plans is crucial for advancing low-carbon city construction and achieving the carbon neutrality goals. Accordingly, this study uses Harbin as a case study, following the "accounting system-benchmark formulation-method construction-result verification" approach to develop a carbon accounting method for urban built-up areas based on space usage activity data. This method transforms the carbon accounting process in urban built-up areas from relying on energy data to focusing on urban spatial elements. The results more accurately demonstrate how urban planning and changes in urban space affect carbon emissions. Building on this, the study proposes using carbon accounting methods to predict urban carbon neutrality and conduct specialized assessments of low-carbon city construction. This supports comprehensive urban planning in central areas aimed at achieving carbon neutrality.

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