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Original Research

Analysis of the Spatio-Temporal Characteristics and Influencing Factors of Carbon Emissions in the Chinese Building Sector

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Abstract

Firstly, the spatial and temporal characteristics of carbon emissions in the Chinese building sector are explored. Secondly, the spatial and temporal heterogeneity of the provincial contributions to carbon emissions in the Chinese building sector and their influencing factors are analyzed. Finally, the spatial and temporal evolution of carbon emissions in the Chinese building sector is projected for the period 2022-2050. The results show that: (1) From 2010 to 2021, carbon emissions in the Chinese buildings still maintain a high growth trend. In addition, building carbon emissions also offer unbalanced features in space. (2) The level of spatial aggregation of carbon emissions from buildings in China is on the rise. (3) The intensity of economic activity and per capita floor area are the main factors driving the increase in carbon emissions in the Chinese buildings, and energy consumption per unit of GDP is the most significant factor mitigating the rise in carbon emissions in the Chinese buildings. The level of contribution of each element to the carbon emissions in the Chinese buildings varies considerably from province to province. (4) Carbon emissions in Chinese building sector will peak at 2.463 $BtCO_2$ in 2036.

Keywords: building carbon emissions, spatial-temporal characteristics, distribution dynamics, provincial contribution, Kaya-LMDI decomposition

Introduction

In the 21st century, resource and environmental constraints, climate change, and other issues have become global challenges. The focus on promoting the "carbon peaking and carbon neutrality" process has become a significant issue for the Chinese government to build a Community of Shared Future for Mankind. The building sector is one of the three major global CO_2 emission sectors (industry, transportation, and building). It is the sector with the fastest-growing carbon emissions and the tremendous potential for carbon reduction [1-2]. Currently, carbon emissions in the Chinese building sector account for 35% to 50% of the total carbon emissions of the whole society [3]. With the development of social and economic development and the improvement of residents' living standards, carbon emissions from buildings will continue to grow rigidly for quite some time [4].

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Therefore, the key to achieving the goal of "carbon peaking and carbon neutrality" in China is to accurately identify the priorities of building carbon emission reduction in each region and to design building carbon reduction policies in a targeted manner.

From the perspective of existing research, scholars' studies on building carbon emissions mainly focus on the accounting of building carbon emissions [5], the analysis of factors influencing building carbon emissions [6], and the study of future building carbon emission pathways [7]. Specifically, in accounting for carbon emissions from buildings, there are currently two mainstream accounting methods in the academic community. One is the top-down accounting method represented by Wang [8], Cai [9], and Huo [10]. The other is the bottom-up accounting method described by Yang [11], Zhou [12], and Peng [13]. In terms of the analysis of factors influencing building carbon emissions, scholars have used the Kaya constant equation [14], the STIRPAT model [15], the exponential decomposition method [16], and the structural decomposition analysis [17] as the main tools to analyze the influencing factors of carbon emissions in the Chinese building sector at the provincial level. In addition, some scholars have used the input-output method [18] and computable general equilibrium model [19] to analyze the factors influencing carbon emissions in the building sector. Based on these approaches, scholars have analyzed the impact of economic growth [20-21], urbanization [22-23], residential income [24-25], floor area [26-27], residential energy use behavior [28-30], climatic conditions [31], building type [32], and indoor comfort [33] on carbon emissions in the building sector. For the modeling of future carbon emission pathways in the building sector, scholars have used the IPAT model and its extensions [34-36], the EKC theoretical model [37], general equilibrium models [19], or by aggregating from bottom to top to obtain end-use energy consumption [38]. Based on the above approach, scholars have introduced scenario analysis to predict the future evolution of carbon emissions in the building sector. For example, Tsinghua University [39] and YANG [40] used scenario analysis to predict the energy consumption and carbon emissions of China's building operation phase in 2030. In addition, other scholars have introduced Monte Carlo simulations to predict carbon emissions in the building sector to make the results more scientific. For example, Ma [41] used dynamic scenario analysis to predict that carbon emissions in Chinese residential buildings will peak at 1.419 (±0.81) $BtCO_2$ in 2037 (±4). Currently, some scholars are beginning to focus on building spatial and temporal characteristics of carbon emissions. For example, Du [42] studied the spatial and temporal characteristics of factors influencing carbon emissions in the public building sector in China from 2008-2019. Li [43] studied the spatial and temporal variation of carbon emission reduction in commercial buildings in China from 2001-2016. In summary, many results have been achieved in research on the accounting, analysis of influencing factors, and emission pathways of carbon emissions in the Chinese building sector. However, less has been done on the spatial and temporal variation of carbon emissions in the Chinese building sector.

To fill the gaps in the above studies and to differentiate from the existing literature, this paper accounts for carbon emissions in the building sector in 30 provinces (municipalities and autonomous regions) of China based on an energy balance sheet splitting model. Exploratory spatial data analysis was used to analyze the spatial correlation characteristics of carbon emissions in the Chinese building sector. Gaussian kernel density estimation was used to portray the spatial differences and dynamic evolution of building carbon emissions at different spatial scales. The spatial and temporal heterogeneity of the sub-provincial contribution of carbon emissions in the Chinese building sector and its influencing factors were analyzed using the Kaya-LMDI decomposition method. The spatial and temporal evolution of carbon emissions in the Chinese building sector from 2022 to 2050 was projected using the Kaya constant equation and based on provincial government plans and related historic trends.

The most important contribution of this study is that, to our knowledge, it is one of the few studies on the spatial and temporal characteristics of carbon emissions during the operation of buildings in China. The results of this study can provide a fundamental basis for the government to grasp the basic situation of carbon emissions in the Chinese building sector, clarify the spatial and temporal characteristics of carbon emissions in the Chinese building sector, and precise control of building energy saving and emission reduction.

Data Sources and Research Methodology

Conceptual Definition and Research Scope

The carbon emissions in the building sector explored in this paper refer to the carbon emissions generated by external energy inputs during the operational phase of a building, including carbon emissions from maintaining the built environment and carbon emissions from various in-building activities. The main types of energy include: coal, oil, natural gas (primary energy) and Thermal and Electricity (secondary energy). Carbon emissions in the building sector can be categorised by building type into carbon emissions in the public building sector, carbon emissions in the urban residential building sector, and carbon emissions in the rural residential building sector.

Data Sources

This study's energy consumption data were taken from the China Energy Statistical Yearbook 2011-2022. The population and economic data involved in the study were taken from the China Statistical Yearbook 2011-2022.

Carbon Emissions Accounting Methods by Province

The calculation method based on the energy balance sheet split model is based on data from the statistical yearbook, which has the advantages of an authoritative source and easy access to time series data [44]. Therefore, a method based on an energy balance sheet split model was chosen to account for national and province carbon emissions in the Chinese building sector. Firstly, the article accounts for total carbon emissions in the Chinese building sector nationally by referring to the methodology provided in the literature [45] and then accounts for carbon emissions in the Chinese building sector of each province. Fig. 1 gives a split model of carbon emissions in the Chinese building sector by province. The formula for calculating total carbon emissions in the Chinese building sector by province [46] is shown in Equation (1-8).

$$C_i = C_{ci} + C_{ui} + C_{ri} + C_{Bi} = \sum E_{communalij} \cdot k_{ij} + \sum E_{urbanij} \cdot k_{ij} + \sum E_{ruralij} \cdot k_{ij} + C_{Bi} \tag{1}$$

$$E_{communal} = \sum_j E_{communalij} = E_{ci} + E_{oi} - TE_{ci} + EH_{ci} + BE_{tspi} \tag{2}$$

$$E_{urbani} = \sum_j E_{urbanij} = E_{uli} - TE_{ui} + EH_{ui} \tag{3}$$

$$E_{rurali} = \sum_j E_{ruralij} = E_{rli} - TE_{ri} \tag{4}$$

$$C_{Bi} = (C - \sum C_i) \cdot \frac{P_i}{P} \tag{5}$$

$$TE_i = 0.95 \cdot (IE_{gi} + CE_{gi} + PE_{gi}) + 0.35 \cdot (IE_{di} + CE_{di} + PE_{di}) + 0.95 \cdot LE_{di} + LE_{gi} + AE_{gi} \tag{6}$$

$$EH_i = \begin{cases} EH_{si} - EH_{ci} - EH_{li} - EH_{oi}, & \text{(Province i is a heating province)} \\ 0, & \text{(Province i is not a heating province)} \end{cases} \tag{7}$$

$$BE_{tspi} = TSPE_{ci} + TSPE_{ei} - EV_{ri} - EV_{p1i} - EV_{p2i} \tag{8}$$

Table 1. Nomenclature.

$BtCO_2$	Billion tons of carbon dioxide
C_i	Carbon emissions of the building sector of each province
C_{ci}	Carbon emissions of public buildings of each province
C_{ui}	Carbon emissions of urban residential buildings of each province
C_{ri}	Carbon emissions of rural residential buildings of each province
C_{Bi}	Carbon balance of the building sector of each province
C	Carbon emissions of the Chinese building sector
P_i	Population size of each province
E_{cij}	All types of energy consumption of public buildings of each province
E_{uij}	All types of energy consumption of urban residential buildings of each province
E_{rij}	All types of energy consumption of rural residential buildings of each province
k_i	Carbon emission factors for all types of energy of each province
E_{ci}	Energy consumption of public buildings of each province
E_{ui}	Energy consumption of urban residential buildings of each province
E_{ri}	Energy consumption of rural residential buildings of each province
E_{wrhci}	Energy consumption in the wholesale, retail trades, hotels, and catering of each province
H_{oi}	Energy consumption of other sectors of each province
TE_{ci}	Deduction of traffic energy consumption apportioned to public buildings of each province
EH_{ci}	Correction of building heating energy consumption apportioned to public buildings of each province
BP_{spi}	Energy consumption of buildings in the transport, storage, and post of each province

E_{uli}	Energy consumption of urban residents of each province
TH_{ui}	Deduction of traffic energy consumption apportioned to urban residential buildings of each province
EH_{ui}	Correction of building heating energy consumption apportioned to urban residential buildings of each province
E_{rli}	Energy consumption of rural residents of each province
TE_{ri}	Deduction of traffic energy consumption apportioned to rural residential buildings of each province
TE_{i}	Deduction of traffic energy consumption of each province
IE_{gi}	Gasoline consumption of industry of each province
CE_{gi}	Gasoline consumption of commerce of each province
PE_{gi}	Gasoline consumption of public services of each province
IE_{di}	Diesel consumption in the industry of each province
CE_{di}	Diesel consumption of commerce of each province
PE_{di}	Diesel consumption of public services of each province
LE_{di}	Diesel consumption of residents of each province
LE_{gi}	Gasoline consumption of residents of each province
AE_{gi}	Gasoline consumption of agriculture of each province
EH_{i}	Correction of building heating energy consumption of each province
EH_{si}	Energy consumption in central heating in Shandong Province of each province
EH_{wrhci}	Heat consumption in wholesale, retail trades, hotels, and catering of each province
EH_{li}	Heat consumption of residents of each province
EH_{oi}	Heat consumption of other sectors of each province
$TSPE_{ci}$	Coal consumption of transport, storage, and post of each province
$TSPE_{ei}$	Electricity consumption of transport, storage, and post of each province
EV_{ri}	Electricity consumption of electrified railways of each province
EV_{p2i}	Electricity consumption in pipeline transport of each province
EV_{p1i}	Electricity consumption in public transport of each province
I_{GM}	Global Moran Index
I_{LM}	Local Moran Index
X_{i}	Province i
X_{j}	Province j
n	Total number of provinces in the study area
W_{ij}	The spatial adjacency weight matrix
h	Bandwidth
$K(\cdot)$	Kernel density function
x_{i}	Value of the observation point
x	Mean value of all observation points
E_{i}	Energy consumption of buildings of each province
GDP_{i}	GDP of each province
F_{i}	Floor space of buildings of each province
e_{i}	Energy consumption per unit GDP of buildings of each province
I_{i}	Economic activity intensity of each province
f_{i}	Floor space per capita of buildings of each province
K_{i}	Integrated carbon emissions factor of buildings of each province

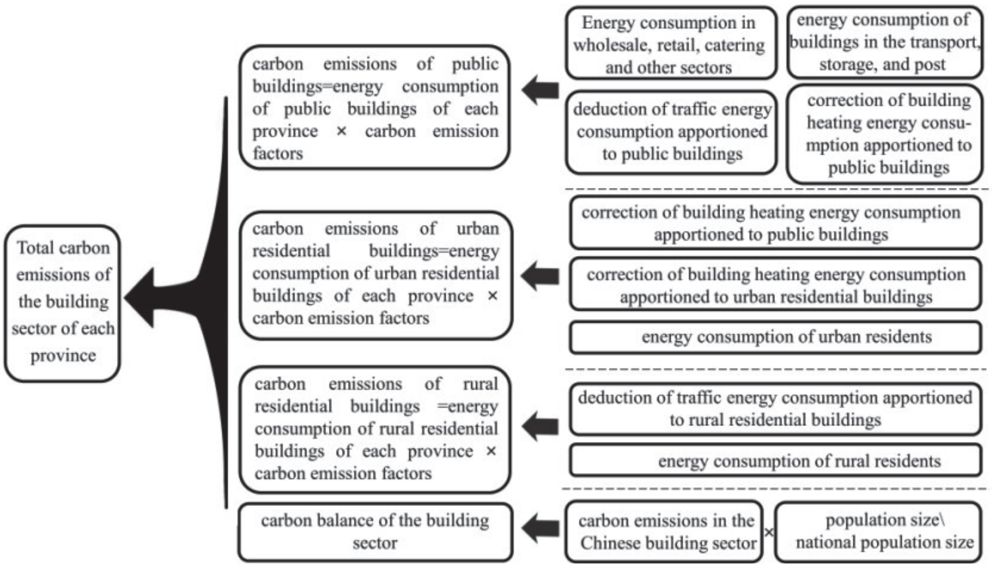

Fig. 1. Carbon emissions consumption splitting model in the residential buildings.

Spatial Autocorrelation Analysis Model

To obtain specific spatial correlation characteristics of Chinese carbon emissions in the Chinese building sector, this paper uses spatial autocorrelation to analyze the spatial correlation characteristics of Chinese carbon emissions in the Chinese building sector from 2010-2019. The global spatial autocorrelation uses the global Moran index as a metric, as shown in Equation (9) [47].

$$I = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}(X_i - \overline{X})(X_j - \overline{X})}{\frac{1}{n}\sum_{i=1}^{n}(X_i - \overline{X})^2 \sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}} \tag{9}$$

Local spatial autocorrelation uses the local Moran index as a metric to further identify the aggregation of carbon emissions in the Chinese building sector in a local area, which is calculated by the formula shown in Equation (10) [48].

$$I_{LM} = \frac{n(X_i - \overline{X})\sum_{j=1}^{n}(X_j - \overline{X})}{\sum_{i=1}^{n}(X_i - \overline{X})^2} \tag{10}$$

Dynamic Evaluation Analysis Model

Kernel density analysis for non-parametric estimation provides an approximate estimate of the probability density of a random variable. It allows the spatial characteristics of carbon emissions in the Chinese building sector in each province to be introduced into the time axis, which in turn portrays the spatial differences and dynamic evolution of carbon emissions in the Chinese building sector at different spatial scales [49]. The formula for its calculation is shown in Equation (11).

$$f(x) = \frac{1}{nh}\sum_{i=1}^{n} K\left(\frac{x_i - x}{h}\right) \tag{11}$$

In the article, a Gaussian kernel function is chosen for estimation, and its expression is shown in Equation (12).

$$K(x) = \frac{1}{\sqrt{2\pi}} \cdot \exp\left(-\frac{x^2}{2}\right) \tag{12}$$

Kaya-LMDI Model

Kaya Identity

As the dominant tool for analyzing the factors influencing carbon emissions, the Kaya identity can decompose the various direct drivers influencing carbon emissions changes and precisely quantify each element's contribution [50]. Based on this analytical framework, this paper selects five categories of influencing factors: population size, energy consumption per unit of GDP, intensity of economic activity, per capita floor area, and comprehensive carbon emission factors to construct the Kaya identity for carbon emissions in the Chinese building sector in each province. The results are shown in Equation (13).

$$C_i = P_i \cdot \frac{E_i}{GDP_i} \cdot \frac{GDP_i}{F_i} \cdot \frac{F_i}{P_i} \cdot \frac{C_i}{E_i} = P_i \cdot e_i \cdot I_i \cdot f_i \cdot K_i \tag{13}$$

LMDI Decomposition

The LMDI decomposition method has the advantages of flexible processing methods, unique decomposition results, independent analysis paths, and concise analysis results [51]. Therefore, based on the construction of the Kaya identity, this paper first investigates the time evolution of the contribution of each influencing factor to the level of carbon emissions in the Chinese building sector in China using the LMDI decomposition method. The paper then analyses the contribution of each factor to the national residential carbon emission change in different provinces. The article factors the decomposition of Equation (13) based on the additive form of the LMDI decomposition method, and its decomposition results in the time interval [0, T] are shown in Equation (14).

$$\Delta C_i\big|_{0\to T} = C_i\big|_T - C_i\big|_0 = \Delta P_i + \Delta e_i + \Delta I_i + \Delta f_i + \Delta K_i \quad (14)$$

Each variable at the right end of Equation (14) can be further expressed in the form shown in Equation (15) to reflect the contribution of different influences to carbon emissions in the Chinese building sector in each province. Here, we use population size as an example to illustrate.

$$\Delta P_i = L(C_i\big|_T, C_i\big|_0)\cdot\ln\left(\frac{P_i\big|_T}{P_i\big|_0}\right), \quad \text{where, } L(a,b) = \begin{cases} \dfrac{a-b}{\ln a - \ln b}, a \neq b \\ 0, a = b \end{cases} \quad (15)$$

At this point, the national carbon emissions in the Chinese building sector can be decomposed as shown in Equation (16).

$$\Delta C\big|_{0\to T} = \Delta P + \Delta e + \Delta I + \Delta f + \Delta K = \sum \Delta P_i + \sum \Delta e_i + \sum \Delta I_i + \sum \Delta f_i + \sum \Delta K_i \quad (16)$$

Carbon Emission Forecasting Models

Static scenario analysis allows the construction of different static scenarios based on the current trends of the variables and the combination of various uncertainties to predict and analyse the evolution of the study subject under different scenarios [44]. In this study, we constructed a model for predicting total carbon emissions in the building sector in each province based on the Kaya constant equation (Equation 13) established in 1.5.1 (Fig. 2). Referring to the study by ZHAO [45], we divided the projection periods into seven. Specifically, they include 2022-2025, 2026-2030, 2031-2035, 2036-2040, 2040-2045, and 2045-2050. We set the values for each factor at each time point based on the provincial government's plans and relevant historical trends. A more detailed reference list of the 30 provinces is shown in Table S1 (Supplementary Material). We then complete the data for the intermediate years based on a polynomial fitting method. After obtaining the parameters for each year, the values are then taken into the model for predicting total carbon emissions from the building sector to obtain the predicted values of carbon emissions in the building sector for each province under different static scenarios.

Results and Analysis

Spatial and Temporal Characteristics of Carbon Emissions in the Chinese Building Sector

The evolution of carbon emissions in the Chinese building sector from 2010-2021 is shown in Fig. 3. Analyzed from the perspective of national carbon

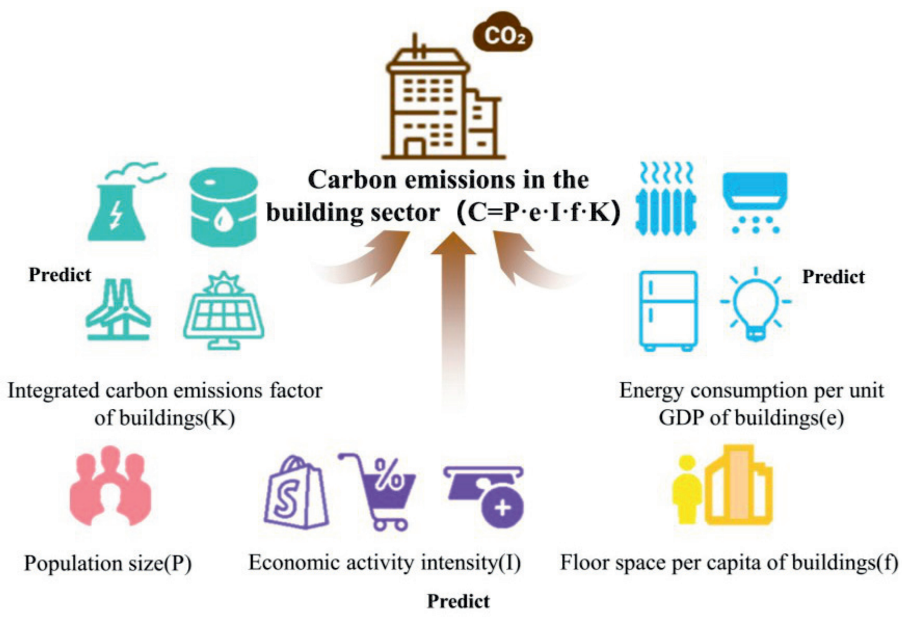

Fig. 2. Predictive model of building carbon emissions.

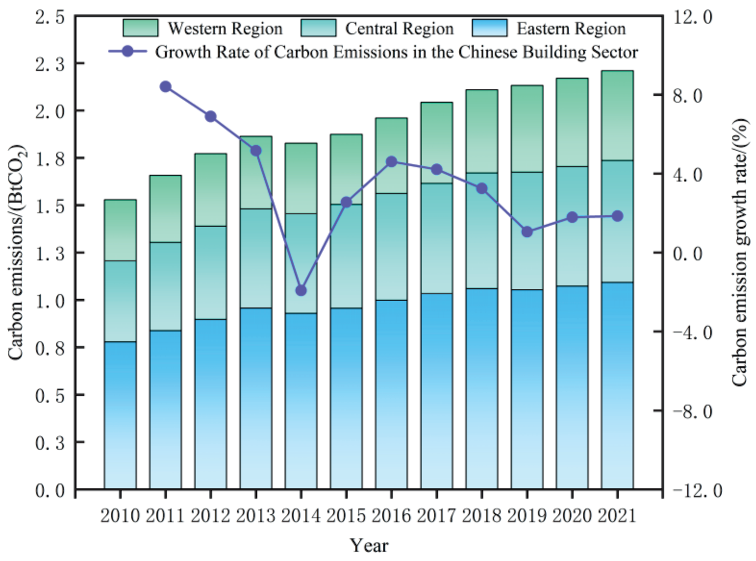

Fig. 3. Evolutionary trend of carbon emissions in the Chinese buildings from 2010 to 2021.

emissions, although carbon emissions in the Chinese building sector fell slightly in 2014 due to the intensive formulation of many energy-saving policies and measures by governments at all levels and the intensification of energy-saving and environmental protection efforts [53], carbon emissions in the Chinese building sector in general still maintained a high growth trend during the sample examination period. By 2021, carbon emissions in the Chinese building sector will reach 2.209 $BtCO_2$, an increase of 0.681 $BtCO_2$, or 44.56%, compared to 2010. As can be seen, carbon emissions in the Chinese building sector are characterized by a large base, rapid growth rate, and difficulty in reaching the peak. Therefore, one of the critical issues the Chinese government urgently needs to address is how to rapidly control carbon emissions in the building sector while ensuring economic development and promoting the achievement of the 2030 carbon peak target on schedule. It is worth noting that since 2011, the growth rate of carbon emissions in the building sector has shown a fluctuating downward trend. This trend indicates that the government's efforts to reduce energy consumption and emissions in the building sector have begun to bear fruit and that carbon emissions in the Chinese building sector have shown a trend toward peaking. Analyzed from the perspective of the spatial distribution of carbon emissions, carbon emissions in the Chinese building sector show uneven and uneven characteristics in space. In 2021, for example, the carbon emissions from buildings in the eastern, central, and western regions will be 1.092 $BtCO_2$, 0.643 $BtCO_2$, and 0.474 $BtCO_2$. They account for 49.43%, 29.11%, and 21.46% of the total carbon emissions in the Chinese building sector, respectively. Therefore, the government's efforts to reduce carbon emissions in the building should focus on the eastern region.

Spatial Correlation Characteristics of Carbon Emissions in the Chinese Building Sector

Global Spatial Autocorrelation of Carbon Emissions in the Chinese Building Sector

The results of the Global Moran' I calculation and significance test for carbon emissions in the Chinese building sector from 2010-2021 using ArcGIS are shown in Table 2. We found that in the twelve sample years selected, all Z values were greater than 2.58, and the Global Moran' I all passed the significance level test at the 99% confidence level. This indicates a robust spatial dependence on carbon emissions in the building sector among provinces. In addition, the Global Moran' I is greater than zero in all years. It shows an increasing trend, indicating that carbon emissions in the Chinese building sector show an apparent positive autocorrelation in space, and the spatial aggregation of building carbon emissions is increasing.

Local Spatial Autocorrelation of Carbon Emissions in the Chinese Building Sector

The article used ArcGIS to conduct a local spatial autocorrelation analysis of carbon emissions in the Chinese building sector to analyze further the spatial correlation of carbon emissions in the Chinese building sector from 2010-2021. The results are shown in Fig. 4. It can be found that from 2010 to 2021, carbon emissions in the Chinese building sector were mainly dominated by high-high (H-H) aggregation and low-low (L-L) aggregation in space, and their distribution pattern is relatively stable. Among them, Shandong Province, Hebei Province, and Henan Province have been in H-H aggregation areas, and Shanxi Province has also been in H-H aggregation since 2013. This indicates that the North China region, represented by Shandong

Table 2. Global Moran'I and its test of the carbon emissions in the Chinese buildings from 2010 to 2021.

Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Moran's I	0.26	0.24	0.26	0.30	0.32	0.32	0.33	0.33	0.34	0.34	0.34	0.35
Z score	2.71	2.48	2.66	3.04	3.24	3.25	3.27	3.34	3.42	3.45	3.46	3.46
P	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Province, Hebei Province, and Henan Province, is the high-value center of carbon emissions in the Chinese building sector during the sample examination period. The government is expected to focus on efforts to control carbon emissions from buildings in the region. Combining the studies of Wu [54] and Zhang [4] the article concluded that the large population size, the traditional and crude energy use, and the high energy consumption of coal-fired heating are essential reasons for the high carbon emissions from buildings in northern China. In contrast, the L-L aggregation areas of carbon emissions in the Chinese building sector are mainly located in the western region, represented by Gansu, Sichuan, and Guizhou provinces. This is due to the backward economic development of the western region, the low standard of living, the resulting low penetration of HVAC systems in buildings, a large number of high energy-consuming household appliances, and the low energy demand of the people. Guangdong Province was a high-low (H-L) agglomeration area from 2010 to 2012 and has shown no significant accumulation since then. This is closely related to the fact that after becoming the first low-carbon pilot to lead the national carbon reduction initiative in 2010, the Guangdong government has been vigorously promoting building energy efficiency and green buildings, focusing on optimizing the energy structure and boosting energy and carbon reduction in the building sector [55]. In addition, Anhui Province changed from a low-high (L-H) agglomeration to a H-H aggregation from 2016-2018 and back again to a L-H accumulation in 2019. This results from a sudden increase in carbon emissions from buildings in Anhui Province starting in 2016, followed by effective control of building carbon emissions.

Dynamic Evolution of Carbon Emissions in the Chinese Building Sector

To further explore the dynamic growth of carbon emissions in the Chinese building sector, the article estimated the Gaussian kernel density of building carbon emissions for the whole country and the eastern, central, and western regions from 2010-2021, and the results are shown in Fig. 5. Analyzed from an overall

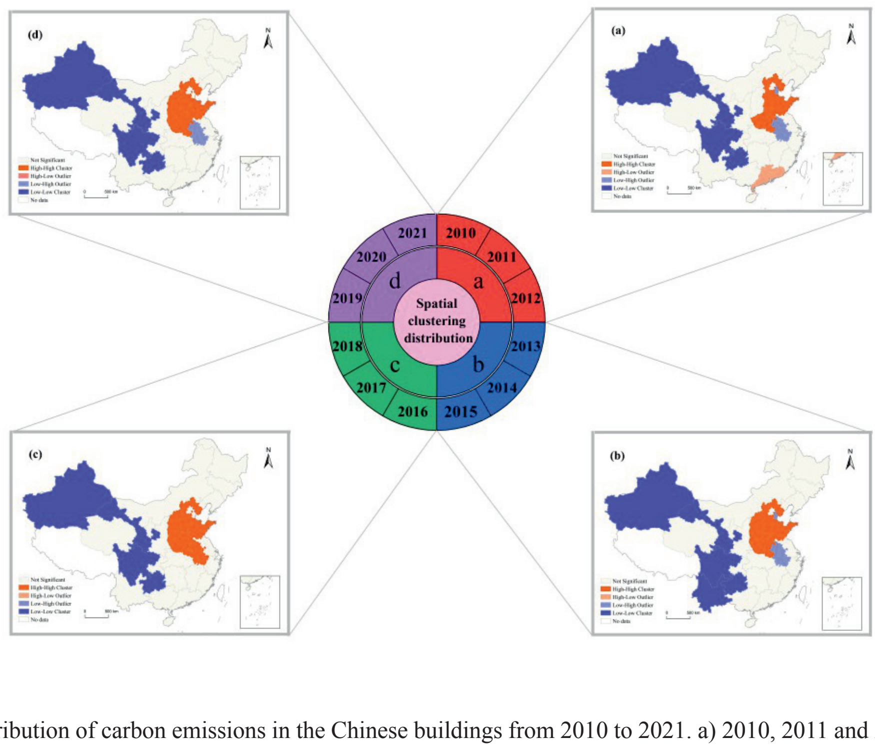

Fig. 4. Spatial clustering distribution of carbon emissions in the Chinese buildings from 2010 to 2021. a) 2010, 2011 and 2012; b) 2013, 2014 and 2015; c) 2016, 2017 and 2018; d) 2019, 2020 and 2021.

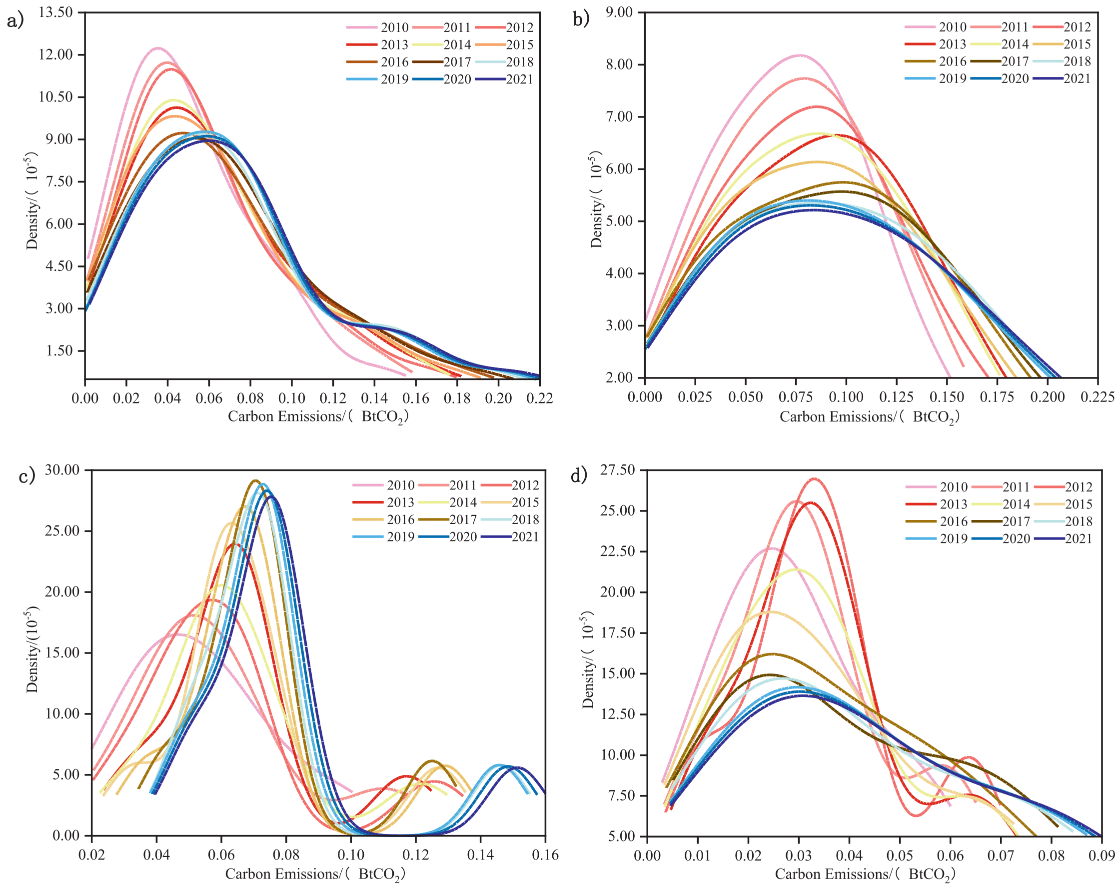

Fig. 5. Dynamic evolutionary characteristics of the distribution of building carbon emissions in different areas from 2010 to 2021. a) National; b) Eastern Region; c) Central Region; d) Western Region.

perspective, carbon emissions in the Chinese building sector show the following main evolutionary features from 2010-2021. Firstly, the kernel density curve for carbon emissions in the Chinese building sector shows an overall continuous shift to the right over the study period. This indicates that carbon emissions in the Chinese building sector have been increasing over the decade. Secondly, the crest of the kernel density curve decreases and widens significantly, and there is a straightforward right-hand drag. This indicates significant and widening differences between the carbon emissions in the building sector in each province. Also, note that both the speed of the rightward shift of the curve and the magnitude of the slowing of the wave's crest shows the most remarkable change between 2010 and 2013. This suggests that 2010-2013 was both a period of rapid growth in the Chinese building sector and a rapid divergence in carbon emissions in the building sector between provinces. In addition, the kernel density curves show a right-skewed distribution throughout the sample period, and the right-skewed distribution is becoming more pronounced. This indicates that most of the provinces in the country have above-average carbon emissions in the building sector and that the low-emitting provinces have been clustering towards higher carbon emissions.

Similar to the spatial distribution of carbon emissions in the building sector, there are significant differences in the dynamic evolution of carbon emissions in the building sector in different regions of the country. Firstly, the analysis was carried out in terms of the movement of the center of the kernel density function of carbon emissions. The center of the kernel density function in the eastern region showed a constant rightward shift during 2010-2017 and started to move to the left after 2017; the center of the kernel density function in the central region showed a constant rightward shift during the study period; the center of the kernel density function in the western region moved to the right from 2010-2013 and to the 2013-2015 and shifted to the left again in 2015-2021. Taken together, the center of the kernel density function in the western region shows an overall trend towards a rightward shift from 2010 to 2021. This suggests that carbon emissions in the building sector in the eastern provinces continued to converge towards higher carbon emission levels from 2010-2017 before falling back after 2017. From 2010 to 2021, the level of carbon emissions in the building sector in the provinces of the central region has been increasing. Carbon emissions in the building sector in the western provinces fluctuate between 2010 and 2021 but still show an overall trend of convergence towards higher carbon emission levels. Secondly, the analysis is carried out from the perspective of the differences in carbon emissions between provinces. During the period examined in the sample, the height of the prominent peak of the kernel density curve in the eastern region has been decreasing, and the width range has been increasing. In contrast, the prominent peak of the nucleus density curve in the Central region shows a constant trend from broad to sharp peaks during 2010-2021. The kernel density curve for the western region is bounded by 2012 during the study period, with the height of the peak increasing before decreasing. This indicates that the differences in carbon emissions in the building sector among the provinces in the eastern region are increasing. From 2010 to 2021, the carbon emissions of the provinces in the western region will gradually change from convergence to divergence. From the perspective of the aggregation of carbon emissions, from 2010 to 2021, carbon emissions in the eastern provinces have been left-skewed, and the left-skewed distribution is becoming more and more apparent. In the central region, carbon emissions gradually change from a left-skewed to right-skewed distribution. In contrast to the trend in the central region, carbon emissions in the western provinces are gradually shifting from a right-skewed to a left-skewed distribution. This indicates that most of the provinces in the eastern region have below-average carbon emissions in the building sector and that most are converging towards lower levels of carbon emissions in the building sector. The range of provinces with lower carbon emission levels in the central region is decreasing, and the low-carbon emitting provinces are clustering towards higher carbon emissions. In the western region, the range of provinces with high carbon emission levels is decreasing. Some provinces are beginning to see a convergence of carbon emissions in the building sector toward lower levels. In addition, it is worth noting that the kernel density curve in the central region has changed from a single peak to a double peak since 2011, and the double peak is constantly evident. This indicates that carbon emissions in the building sector in the central provinces have been polarised since 2011, and the trend of polarisation has been increasing.

Spatial and Temporal Heterogeneity of the Sub-Provincial Contribution of Carbon Emissions in the Chinese Building Sector and Its Influencing Factors

Provincial Contribution of Carbon Emissions in the Chinese Building Sector

In order to explore the differences in the level of contribution of each province to the carbon emissions in the Chinese building sector and its changing pattern, this paper calculates the contribution of each province's annual change in carbon emissions to the carbon emissions in the Chinese building sector. When the contribution of a province is positive, the province has a driving effect on the growth of total carbon emissions in the building sector. Conversely, the province dampens the growth of total carbon emissions in the building sector. The specific results are shown in Fig. 6. Overall, the provinces in the eastern region contribute much more to the national carbon emissions in the building sector than the central and western regions. Of the eleven sample years selected, the top provinces in terms of contribution were all in the eastern region, except for 2018 and 2019. At least two of the top three provinces in terms of contribution are located in the eastern region. This result again demonstrates the urgency and importance of carbon reduction efforts in the building sector in the eastern provinces.

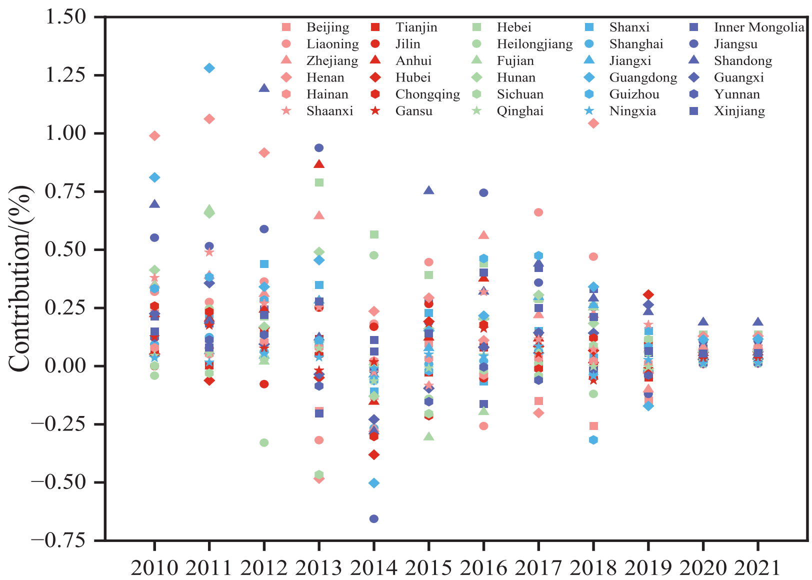

Fig. 6. Provincial contributions of carbon emissions in the Chinese buildings at different stages from 2010 to 2021.

Specifically, the three provinces of Shandong, Jiangsu, and Liaoning are the most significant contributors. All of these provinces were ranked first in terms of each province's contribution to national carbon emissions in the building sector for at least two years during the sample period examined and were ranked in the top three in terms of contribution on several occasions. Therefore, controlling carbon emissions in the building sector by the three provinces of Shandong, Jiangsu, and Liaoning is vital in curbing the growth of carbon emissions in the Chinese building sector. It is worth noting that the difference in the contribution of each province to carbon emissions in the Chinese building sector is becoming smaller between 2011 and 2021. In 2011, the difference between the contribution of the province with the enormous contribution and the province with the minor contribution was 1.34%, and after 2019, this value shrunk to 0.48%.

Time Evolutionary Characteristics of the Influencing Factors

Based on the Kaya-LMDI decomposition method to decompose the factors influencing carbon emissions in the building sector in 2010-2021, the decomposition results are shown in Fig. 7. The intensity of economic activity and per capita floor area contribute much more to the growth of carbon emissions from buildings than other factors and are the main factors driving the increase of carbon emissions in the Chinese building sector. Referring to studies by scholars such as CAI [56], the article analyses that a more vigorous intensity of economic activity directly reflects a higher standard of living for residents. As the standard of living of residents continues to rise, people are placing higher demands on the built environment and living comfort, and the significant increase in energy use by indoor end-use equipment such as HVAC systems makes the intensity of economic activity a significant factor driving carbon emissions in the building sector. At the same time, large-scale property development has made floor space per capita a significant driver of increased carbon emissions in the building sector. It is worth noting that in some years, the level of contribution of economic activity intensity to total carbon emissions in the building sector decreases significantly, with floor area per capita replacing economic activity intensity as the most significant factor driving the increase in total carbon emissions in the building sector, which is associated with the significant increase in total building area during this period. In addition, the size of the population also plays a driving role in the growth of carbon emissions in the building sector. In contrast, due to the increasing level of energy efficiency in buildings and the government's vigorous promotion of building energy efficiency policies [57], energy consumption per unit of GDP contributes negatively to carbon emissions in the Chinese building sector every year, and in most years has a far more dampening effect on carbon emissions in the Chinese building sector than any other factor, being the most significant factor in mitigating the increase in total carbon emissions in the Chinese building sector nationwide. Since 2011, the contribution of the combined carbon emission factor to carbon emissions in the building sector has changed from positive to negative. It has been significantly suppressing carbon emissions in the Chinese building sector. This demonstrates the importance of reducing the combined carbon emission factor in curbing carbon emissions in the building sector and reflects that the policies of Chinese governments at all levels to restructure energy consumption are beginning to bear fruit.

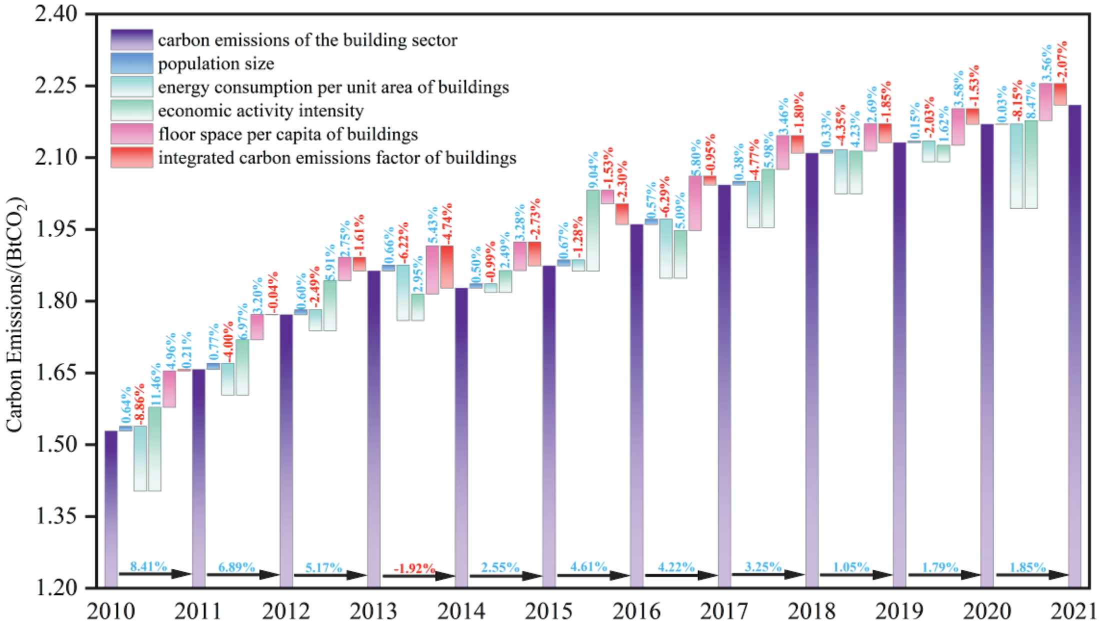

Fig. 7. Results of LMDI decomposition of carbon emissions in the Chinese buildings from 2010 to 2021.

Spatial Heterogeneity of the Influencing Factors

Based on the analysis of the contribution of various factors to the incremental carbon emissions in the Chinese building sector, the article further investigated the contribution of different factors to the national carbon emissions in the building sector in each province. The results (Fig. 8) show that:

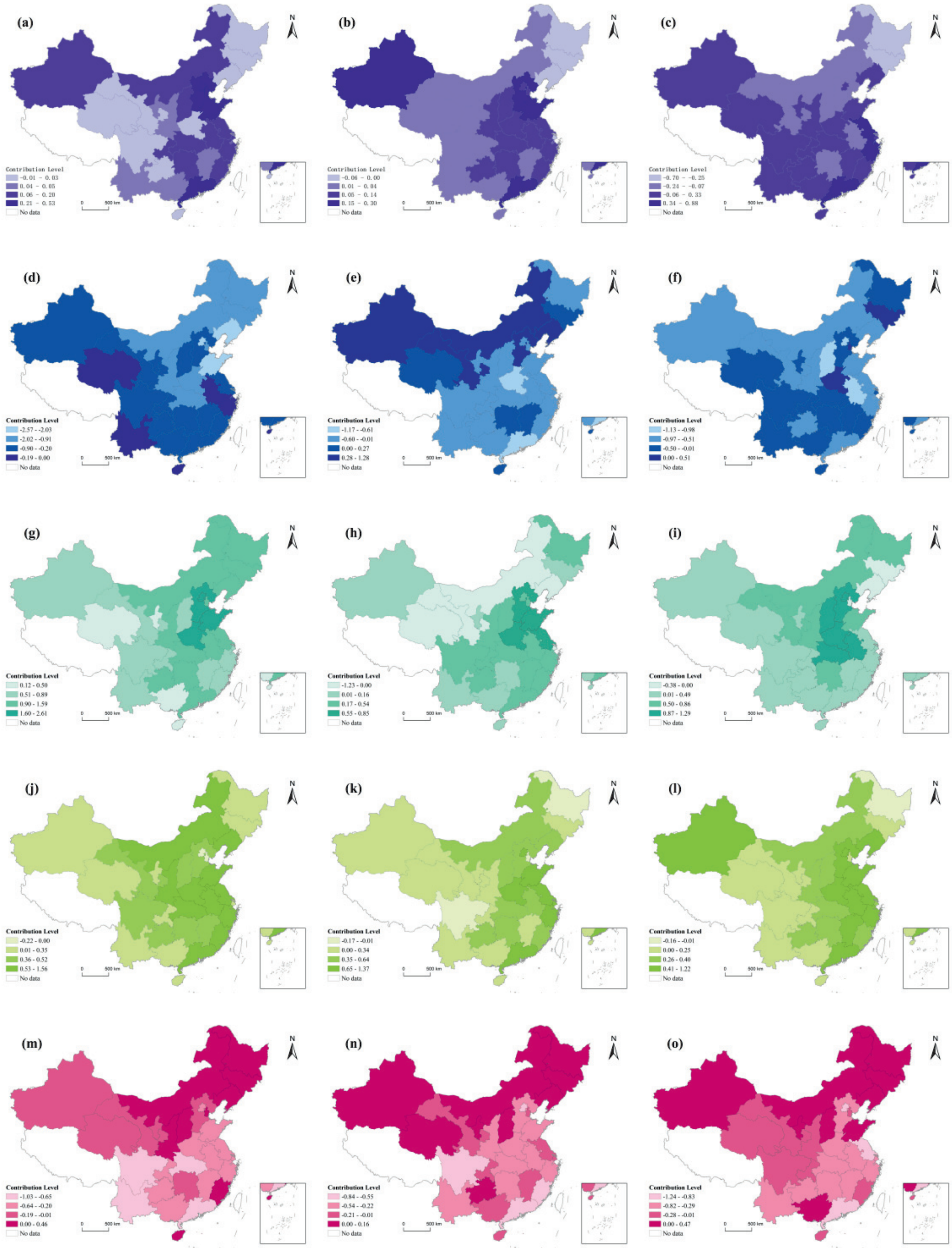

Fig. 8. Spatial heterogeneity of the contribution level of each influencing factor to the carbon emissions in the Chinese buildings. a) Population size, 2010-2014; b) Population size, 2014-2017; c) Population size, 2017-2021; d) energy consumption per unit GDP of buildings, 2010-2014; e) energy consumption per unit GDP of buildings, 2014-2017; f) energy consumption per unit GDP of buildings, 2017-2021; g) economic activity intensity, 2010-2014; h) economic activity intensity, 2014-2017; i) economic activity intensity, 2017-2021; j) floor space per capita of buildings, 2010-2014; (k) floor space per capita of buildings, 2014-2017; l) floor space per capita of buildings, 2017-2021; m) integrated carbon emissions factor of buildings, 2010-2014; n) integrated carbon emissions factor of buildings, 2014-2017; o) integrated carbon emissions factor of buildings, 2017-2021.

(1) The spatial distribution of the contribution of population size to carbon emissions in the Chinese building sector by province is mainly characterized by a high contribution from the east and a low contribution from the west. Among them, the Bohai Rim and Guangdong Province have the most significant role in driving the growth of carbon emissions in the building sector. The geographical location and economic development of these areas, the concentration and growth of the population, and the increasing demand for the number of buildings and the energy used within them have led to increased carbon emissions in the building sector. In addition, the population size of the Xinjiang Uyghur Autonomous Region also contributed significantly to the increase in carbon emissions in the building sector nationwide during the study period. According to statistics, the average annual population growth rate in the Xinjiang Uyghur Autonomous Region from 2010-2021 is 1.41%. The rapid increase in population size makes the population exhibit a significant driving effect on the national carbon emissions in the building sector. After 2014, the size of the population in the Northeast began to have a dampening effect on the increase in carbon emissions in the Chinese building sector. This is associated with the need for economic growth and significant population outflow from the North East in recent years. The contribution of population size to the growth of carbon emissions in the Chinese building sector was low in Henan Province from 2010 to 2014. This may be due to the loss of population due to the attraction of talent to the region from its surrounding economically developed regions, with lower population growth dampening the driving effect of population size on carbon emissions in the building sector.

(2) The spatial distribution pattern of the contribution of energy consumption per unit of GDP to carbon emissions in the Chinese building sector by province varies considerably during the period 2010-2021. However, it is worth noting that during the sample study period, the majority of provinces across the country had a negative contribution of energy consumption per unit of GDP to the carbon emissions in the Chinese building sector, indicating that efforts to control the energy intensity of China's buildings have had some emission reduction effect. In addition, from 2014 to 2017, most provinces in China's northern border had a negative to the positive contribution of energy consumption per unit of GDP to carbon emissions in the Chinese building sector. This may be due to the rapid economic development of the northern border provinces due to national policy support in recent years and the demand for a high quality of living standard brought about by the increase in residents' economic income. This has inevitably led to a rapid increase in consumption per unit of end-use energy in buildings, and it is easy to see how energy consumption per unit of GDP in the vast majority of China's northern border provinces has shifted from a suppressive to a driving effect on carbon emissions in the Chinese building sector.

(3) Northern China was the region where the intensity of economic activity drove the most potent carbon emissions in the Chinese building sector during the sample study period. As one of the most economically developed regions in China, the higher intensity of economic activity in northern China continues to stimulate the consumption of luxurious means of enjoyment, and the increase in energy-intensive products in buildings naturally drives the growth of carbon emissions in the building sector. Between 2014 and 2017, the intensity of economic activity in most northern provinces changed the contribution level to carbon emissions in the Chinese building sector from a positive to a negative value. This is related to the large-scale real estate development in the northern provinces during this period.

(4) The spatial distribution of floor space per capita contribution to carbon emissions in the Chinese building sector by province is mainly characterized by a high contribution from the eastern coastal provinces and a low contribution from the western inland provinces. The analysis suggests that this is related to the strong real estate development and significant area of new housing completions in the eastern coastal areas during the study period, while the western inland areas have less real estate development and smaller area of new housing completions due to economic and other reasons. It is worth noting that since 2014, the per capita floor area in Fujian Province has been a much lower driver of carbon emissions in the Chinese building sector than in other coastal provinces.

(5) From 2010 to 2021, the regions where the combined carbon emission factors contribute positively to carbon emissions in the Chinese building sector are mainly in the northeast and northern frontier regions. This is closely related to the relatively large share of thermal power in the local energy consumption structure, especially the poor energy-saving technologies in winter heating systems. The level of contribution of the combined carbon emission factor to carbon emissions in the Chinese building sector has been negative for most of the southern regions of China during the sample study period. This is related to the increasing share of clean energy use and the optimization of the energy consumption structure in the southern provinces.

Spatial and Temporal Projections of Carbon Emissions in the Chinese Building Sector

Based on the provincial carbon emission projection models constructed in this paper, and after setting the values of each factor at each time point based on the plans of each provincial government and relevant historic trends, the evolution of carbon emissions in the Chinese and provincial building sectors from 2022 to 2050 was obtained (Fig. 9). In terms

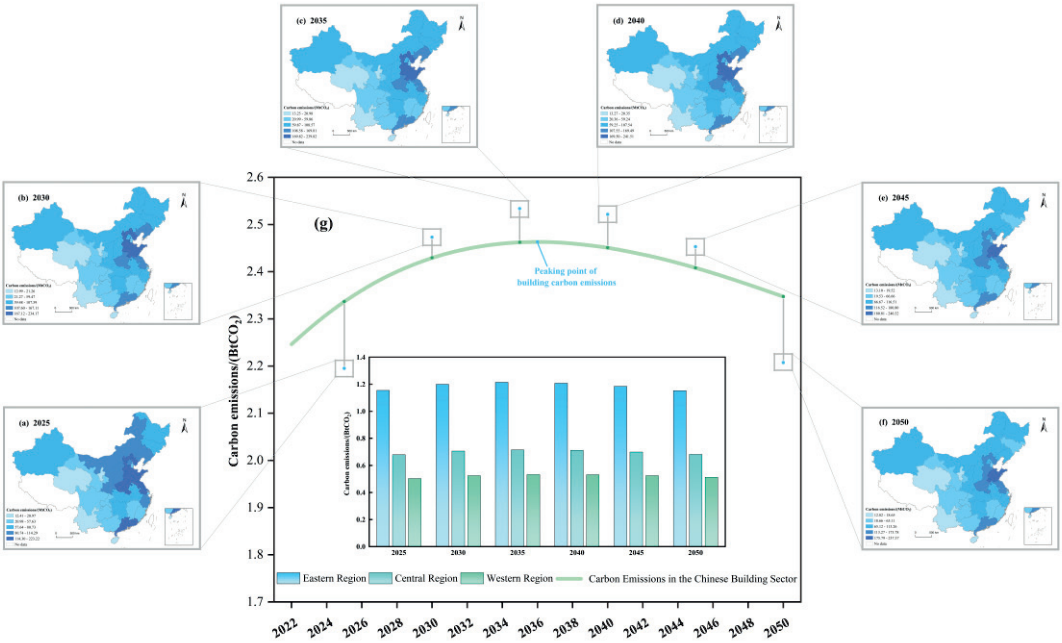

Fig. 9. Projected results on the spatial and temporal evolution of carbon emissions in the Chinese building sector.

of the temporal evolution of total carbon emissions in the Chinese building sector, the total carbon emissions in the Chinese building sector will show an "inverted U-shaped" trend. For a considerable period in the future, carbon emissions in the Chinese building sector will continue to grow at a high rate.In our projection model, the time to peak is much longer than the Chinese government's expected target of 2030. This suggests that the Chinese government should further optimize its energy policies to achieve an early peak in carbon emissions in the Chinese building sector. This result is also consistent with the study of Ma [44]. In terms of the spatial evolution of carbon emissions in the Chinese building sector, the provinces in the eastern region of China will still account for about 50% of carbon emissions in the Chinese building sector during the period 2022-2050, much higher than the carbon emissions in the central and western regions. Therefore, future carbon reduction in the Chinese building sector should focus on the eastern region. The five provinces of Shandong, Jiangsu, Hebei, Henan, and Guangdong will have much higher carbon emissions in the building sector than other regions. Carbon peaking and carbon neutrality in the Chinese building sector will depend on more outstanding efforts from these five provinces.

Conclusion

(1) From the perspective of the spatial and temporal distribution characteristics of building carbon emissions, carbon emissions in the Chinese building sector will continue to grow at a high rate from 2010 to 2021, showing the characteristics of a large base, fast growth rate and difficulty in reaching the peak. In addition, carbon emissions in the Chinese building sector are spatially unbalanced and uneven. In 2021, the eastern region accounts for 49.43% of carbon emissions in the Chinese building sector. The government's efforts to reduce carbon emissions in the building sector should be focused on the eastern region.

(2) Analysis from the perspective of the spatial correlation of carbon emissions in the building sector. Carbon emissions in the Chinese building sector show an apparent positive spatial autocorrelation, and the spatial aggregation of carbon emissions in the building sector is increasing. Among them, the H-H aggregation areas are mainly located in North China, represented by Shandong Province, Hebei Province, and Henan Province. They are the high-value centers of carbon emissions in the Chinese building sector. The L-L agglomeration area is mainly located in the western region, represented by Gansu, Sichuan, and Guizhou provinces. They are the low-value centers of carbon emissions in the Chinese building sector.

(3) An analysis of the dynamic evolution of carbon emissions in the building sector shows significant and widening differences between provinces in terms of carbon emissions in the building sector. 2010-2013 was a period of rapid growth in carbon emissions in the Chinese building sector as well as a period of rapid divergence between provinces in terms of carbon emissions in the building sector. At the same time, there are significant differences in the dynamics of carbon emissions in the building sector across different regions of the country. The differences in carbon emissions in the building sector between provinces in the eastern region are increasing, and most provinces have below-average carbon emissions in the building

sector. The provinces in the central region show a dynamic convergence in carbon emissions, and the provinces with low carbon emissions converge toward higher carbon emissions. In the western region, carbon emissions are gradually changing from convergent to divergent, and in some provinces, emissions in the building sector are beginning to converge towards lower levels. Notably, carbon emissions in the building sector in the central provinces have been polarised since 2011, and the trend of polarisation has been increasing.

(4) Analysis from the perspective of the sub-provincial contribution of carbon emissions in the building sector. The contribution of the eastern provinces to carbon emissions in the Chinese building sector is much higher than that of the central and western regions. Of these, three provinces – Shandong, Jiangsu, and Liaoning – make the most significant contributions. It is worth noting that the difference in the contribution of each province to China's carbon emissions in the building sector from 2011-2021 is becoming smaller.

(5) Analysis from the perspective of the spatial and temporal heterogeneity of factors influencing carbon emissions in the building sector. The intensity of economic activity and per capita floor area are the main factors driving the increase in carbon emissions in the Chinese building sector. Energy consumption per unit of GDP is the most significant factor mitigating the increase in total carbon emissions in the Chinese building sector. In addition, the level of contribution of each factor to the change in carbon emissions in the Chinese building sector varies considerably from province to province due to differences in the actual situation and development conditions of each region. Therefore, the relevant government departments should develop tailored carbon reduction strategies for buildings, depending on the contribution of various factors to the carbon emissions in the building sector in the region. For example, in the northeastern region, attention should be paid to controlling energy intensity in buildings and optimizing the energy consumption structure. In the northern frontier regions, attention should be paid to the guidance of household energy-saving behavior and the strict control of energy-saving standards in new buildings.

(6) Analysis from the perspective of building carbon emissions' future spatial and temporal evolution. The total carbon emissions in the Chinese building sector will show an "inverted U-shaped" trend and peak at 2.463 $BtCO_2$ in 2036. During 2022-2050, the spatial distribution of carbon emissions in the Chinese building sector will remain similar to the current situation, with carbon emissions in the building sector in the eastern region being much higher than those in the central and western regions. In particular, the five provinces of Shandong, Jiangsu, Hebei, Henan, and Guangdong will have much higher carbon emissions in the building sector than the other regions.

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Conflict of Interest

The authors declare no conflict of interest.

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Supplementary Material

Table S1. References for each province in scenario setting.

Provinces	References
Beijing	The 13th five-year plan and 14th five-year plan for Beijing's national economic and social development; The 13th five-year plan and 14th five-year plan for energy development in Beijing; The General Planning for Beijing (2016-2035)
Tianjin	The 13th five-year plan and 14th five-year plan for Tianjin's national economic and social development; The 13th five-year plan and 14th five-year plan for energy development in Tianjin
Hebei	The 13th five-year plan and 14th five-year plan for Hebei's national economic and social development; The 13th five-year plan and 14th five-year plan for energy development in Hebei; The population development plan of Hebei Province (2018-2035)
Shanxi	The 13th five-year plan and 14th five-year plan for Shanxi's national economic and social development; The 13th five-year plan and 14th five-year plan for energy development in Shanxi; The 14th five-year plan for population development in Shanxi
Inner Mongolia	The 13th five-year plan and 14th five-year plan for Inner Mongolia's national economic and social development; The 13th five-year plan and 14th five-year plan for energy development in Inner Mongolia; The 14th five-year plan for population development in Inner Mongolia
Liaoning	The 13th five-year plan and 14th five-year plan for Liaoning's national economic and social development; The 13th five-year plan and 14th five-year plan for energy conservation and emission reduction in Liaoning; The population development plan of Liaoning Province (2016-2030)
Jilin	The 13th five-year plan and 14th five-year plan for Jilin's national economic and social development; The 13th five-year plan and 14th five-year plan for energy development in Jilin
Heilongjiang	The 13th five-year plan and 14th five-year plan for Heilongjiang's national economic and social development; The 13th five-year plan and 14th five-year plan for energy development in Heilongjiang
Shanghai	The 13th five-year plan and 14th five-year plan for Shanghai's national economic and social development; The 13th five-year plan and 14th five-year plan for energy development in Shanghai; The General Planning for Shanghai (2017-2035)
Jiangsu	The 13th five-year plan and 14th five-year plan for Jiangsu's national economic and social development; The 13th five-year plan and 14th five-year plan for energy development in Jiangsu; The 14th five-year plan for population development in Jiangsu
Zhejiang	The 13th five-year plan and 14th five-year plan for Zhejiang's national economic and social development; The 13th five-year plan and 14th five-year plan for energy development in Zhejiang; The 14th five-year plan for population development in Zhejiang

Anhui	The 13th five-year plan and 14th five-year plan for Anhui's national economic and social development; The 13th five-year plan and 14th five-year plan for energy development in Anhui; The 14th five-year plan for population development in Anhui
Fujian	The 13th five-year plan and 14th five-year plan for Fujian's national economic and social development; The 13th five-year plan and 14th five-year plan for energy development in Fujian; The population development plan of Fujian Province (2016-2030)
Jiangxi	The 13th five-year plan and 14th five-year plan for Jiangxi's national economic and social development; The 13th five-year plan and 14th five-year plan for energy development in Jiangxi; The population development plan of Jiangxi Province (2016-2030)
Shandong	The 13th five-year plan and 14th five-year plan for Shandong's national economic and social development; Medium- and long-term energy development plan of Shandong; The 14th five-year plan for population development in Shandong
Henan	The 13th five-year plan and 14th five-year plan for Henan's national economic and social development; The 14th Five-Year Plan modern energy system and carbon peak carbon neutralization plan in Henan; The population development plan of Henan Province (2016-2030)
Hubei	The 13th five-year plan and 14th five-year plan for Hubei's national economic and social development; The 13th five-year plan and 14th five-year plan for energy development in Hubei; The population development plan of Hubei Province (2018-2030)
Hunan	The 13th five-year plan and 14th five-year plan for Hunan's national economic and social development; The 13th five-year plan and 14th five-year plan for energy development in Hunan; The 14th five-year plan for population development in Hunan
Guangdong	The 13th five-year plan and 14th five-year plan for Guangdong's national economic and social development; The 13th five-year plan and 14th five-year plan for energy development in Guangdong; The population development plan of Guangdong Province (2017-2030)
Guangxi	The 13th five-year plan and 14th five-year plan for Guangxi's national economic and social development; The 13th five-year plan and 14th five-year plan for energy development in Guangxi; The population development plan of Guangxi Province (2016-2030)
Hainan	The 13th five-year plan and 14th five-year plan for Hainan's national economic and social development; The 13th five-year plan and 14th five-year plan for energy development in Hainan; The population development plan of Hainan Province (2030)
Chongqing	The 13th five-year plan and 14th five-year plan for Chongqing's national economic and social development; The 13th five-year plan and 14th five-year plan for energy development in Chongqing; The population development plan of Chongqing (2016-2030)
Sichuan	The 13th five-year plan and 14th five-year plan for Sichuan's national economic and social development; The 13th five-year plan and 14th five-year plan for energy development in Sichuan; The 14th five-year plan for population development in Sichuan; The urban system planning of Sichuan Province (2014-2030)
Guizhou	The 13th five-year plan and 14th five-year plan for Guizhou's national economic and social development; The 13th five-year plan and 14th five-year plan for energy development in Guizhou; The 14th five-year plan for population development in Guizhou
Yunnan	The 13th five-year plan and 14th five-year plan for Yunnan's national economic and social development; The energy development plan of Yunnan Province (2016-2020); The urban system planning of Yunnan Province (2011-2030)
Shaanxi	The 13th five-year plan and 14th five-year plan for Shaanxi's national economic and social development; The 13th five-year plan and 14th five-year plan for energy conservation and emission reduction in Shaanxi; The population development plan of Shaanxi Province (2016-2030)
Gansu	The 13th five-year plan and 14th five-year plan for Gansu's national economic and social development; The 13th five-year plan and 14th five-year plan for energy development in Gansu; The population development plan of Gansu Province (2016-2030)
Qinghai	The 13th five-year plan and 14th five-year plan for Qinghai's national economic and social development; The 13th five-year plan and 14th five-year plan for energy development in Qinghai; The urban system planning of Qinghai Province (2015-2030)
Ningxia	The 13th five-year plan and 14th five-year plan for Ningxia's national economic and social development; The 13th five-year plan and 14th five-year plan for energy development in Ningxia; The 13th five-year plan and 14th five-year plan for the balanced development of health and family planning and population in Ningxia
Xinjiang	The 13th five-year plan and 14th five-year plan for Xinjiang's national economic and social development; The 13th five-year plan and 14th five-year plan for energy development in Xinjiang; The urban system planning of Xinjiang Province (2015-2030)