Spatial and Temporal Trends of Carbon Emissions Caused by Buildings in China

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Abstract. Carbon emission caused by buildings is an important source of regional carbon emission, and it changes with time and space. This is due to the agglomeration effect of economic and construction industry development. Meanwhile, climates in different regions also have great differences in energy consumption. The effects of space and time on carbon emissions in different regions should be noticed to discover the development trend of building carbon emissions. Therefore, the GTWR model, which can find the changes of carbon emissions in time and space at different stages, is applied to study the influence of space-time effect on the carbon emissions in the whole life cycle of buildings. This will be conducive to the discovery of key driving factors of building carbon emissions and thus provide an effective and feasible path for energy conservation and emission reduction.

Keywords: Buildings · Carbon emission · GTWR · spatial clustering

1 Introduction

Carbon emission caused by buildings is an important source of regional carbon emission (Zhang, Hu, Guo, Mastrucci, Zhang, Yang and Yan, 2022), and it changes with time and space. This is due to the agglomeration effect of economic and construction industry development. Meanwhile, regions with different climates also have great differences in energy consumption (Zhang, Yan, Hu and Guo, 2019). The influence of such differences on carbon emissions in different regions should be noticed to discover the development trend of building carbon emissions (Wang, Du and Liu, 2022).

2 Methodology

2.1 Calculation of Building Carbon Emissions

The whole life cycle of the building consists of several stages, including the production of building materials, transportation of building materials, construction, construction operation and demolition of building materials (Tan, Lai, Gu, Zeng and Li, 2018). This

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paper calculates the life-cycle carbon emissions of the construction industry by combining LCA and IPCC method (Rodrigues, Martins, Nunes, Quintas, Mata and Caetano, 2018).

1. Carbon emissions from building materials production

   Studies show that the carbon emission of steel, cement, wood, glass and aluminum accounts for more than 90% of the carbon emission of building materials (Li, Xie, Xu, Li, Jim and Wei, 2022). Therefore, carbon emission of building materials production is as follows:

$$CC_1 = \sum_{i=1}^{n} m_i \times me_i \tag{1}$$

   where, m_i represents the consumption of the ith building material, and me_i represents the carbon emission coefficient of the ith building material.

2. Carbon emissions from building materials transportation

   As goods, building materials may be transported in different ways, so their carbon emissions during the transport stage are calculated as follows:

$$CC_2 = \sum_{i=1}^{n} \sum_{j}^{m} m_i \times d_i \times te_j \tag{2}$$

   where, m_i represents the consumption of the ith type of building materials, d_i represents the transportation distance of the ith type of building materials, and te_j represents the carbon emission factor of the jth mode of transportation.

3. Carbon emissions from construction

   Carbon emissions in the construction phase include two parts: direct carbon emissions from the use of fossil fuels, and indirect carbon emissions from the use of heat and electricity in the construction process. In summary, all carbon emissions can be calculated in terms of energy use and emission factors (Peng, 2016), and the formula is as follows:

$$CC_3 = \sum_{i=1}^{n} e_i \times ee_i \tag{3}$$

   where e_i represents the consumption of the ith energy, and ee_i represents the carbon emission factor of the ith energy.

4. Carbon emissions from building operations

   The carbon emission in the building operation stage is similar to that in the construction stage, which can be divided into direct fuel carbon emission and indirect carbon emission (Zhang, Luo, Liu, Feng, Zhou and Yang, 2022). The specific calculation method is as follows:

$$CC_4 = \sum_{i=1}^{n} \sum_{j}^{m} e_i \times ee_i \times cr_{ij} \tag{4}$$

   where e_i represents the consumption of the ith energy, ee_i represents the carbon emission factor of the ith energy, cr_{ij} represents the accounting proportion of the carbon emission of the ith energy in the jth sector (Huo, Li, Cai, Zuo, Jia and Wei, 2020).

2.2 Spatial and Temporal Analysis of Building Carbon Emission

1. Data preprocessing

   In the past studies on carbon emissions, carbon emissions in the production, transportation and construction stages of building materials before the building is put into operation are usually studied together (Zhang, Jiang, Cui and Skitmore, 2022). It is usually called to as embodied carbon emissions. Carbon emissions in embodied stages and some indicators of carbon emissions in operational stages are mainly considered here, as shown in Table 1.

2. Spatial analysis model

   Spatial autocorrelation is related to the average deviation of target attributes of adjacent locations in space, it is mainly measured by Moran's I (Huo, Li, Cai, Zuo, Jia and Wei, 2020). Moran's I is calculated by the following formula:

$$I = \frac{n}{S} \cdot \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij} z_{ij} z_j}{\sum_{i=1}^{n} w_i^2} \tag{5}$$

$$S = \sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij} \tag{6}$$

   where, I represents the Moran's I, n represents the total number of spatial units studied, z_i and z_j are the deviations between the attributes of the ith and jth regions and the mean values of the attributes, z_j represents the geographical weights between the ith and jth regions, and S is the aggregation of spatial weights.
3. GTWR model

   GTWR provides a way to consider time and space distance as function parameters, which is closer to the objective law, thus improving the accuracy of fitting (Wang, Du and Liu, 2022).

$$d_{ij} = \sqrt{\lambda\left[\left(u_i - u_j\right)^2 + \left(v_i - v_j\right)^2 + \mu\left(t_i - t_j\right)^2\right]} \tag{7}$$

$$y_i = \beta_0(u_i, v_i, t_i) + \sum_{k=1}^{p} \beta_k(u_i, v_i, t_i) x_{ik} + \varepsilon_i \tag{8}$$

Table 1. Construction operation phase accounting scope

Variables		Abb	Unit
Dependent variable	Building life cycle carbon emissions	CC	kg
Independent variable	Carbon emissions per capita in embodied stage	ECP	Kg/person
	Per capita construction area	EAP	m^2/person
	Carbon emission per unit area in embodied stage	ECI	Kg/m^2
	Carbon emissions per capita in operation stage	OCP	Kg/person
	Per capita floor area	OAP	m^2/person
	Carbon emission per unit area in operation stage	OCI	Kg/m^2

$$d_{st} = \lambda d_s + \mu d_t \tag{9}$$

where, y_i represents the value of position i, (u_i, v_i) represents coordinates of position i in t_i, $\beta_0(u_i, v_i)$ and $\beta_k(u_i, v_i)$ are the intercepts and local coefficients of position i in t_i, respectively, p is the number of factors, x_{ik} represents the independent variable at position i, and ε_i represents the random error term. d_s and d_t represent distances in time and space dimensions respectively.

3 Results and Discussion

3.1 Carbon Emission Calculation Results

Based on the data of China Statistical Yearbook and other data and the calculation of carbon emissions at different stages of the whole life cycle of buildings in different regions of China in Formula (1)–(4), the carbon emission distribution of the whole life cycle of buildings in China can be obtained.

As can be seen from Fig. 1, the life-cycle carbon emission of the construction industry increased steadily from 2002 to 2007, accelerated from 2007, further increased in 2010, reached the peak in 2012, and then entered a period of shock, but did not exceed the maximum value in 2012.

The carbon emission proportion of building materials production stage is the highest, so the trend of carbon emission of the whole life cycle is very close to that of building materials production. The carbon emissions in the construction operation stage accounted for the second place, and the carbon emissions in the construction operation stage began to rise after 2012. The carbon emission of building materials transportation and construction is relatively low, the carbon emission of building materials transportation is about 4%–8%, and the carbon emission of construction is about 1–2%.

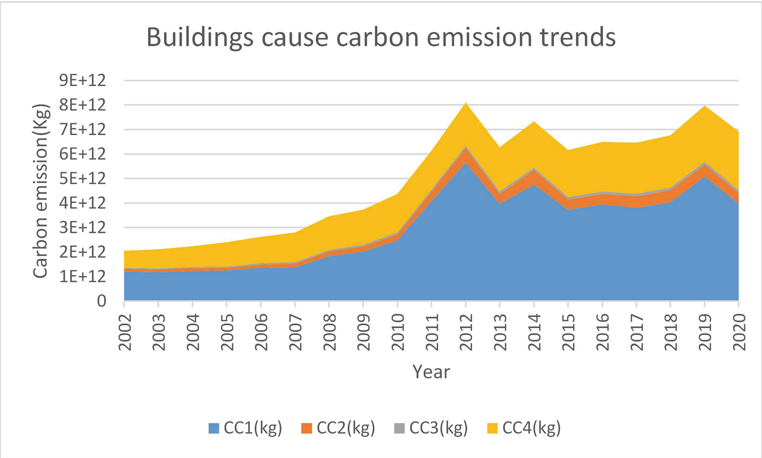


Fig. 1. Trend of carbon emissions caused by buildings

3.2 Spatial Correlation Evaluation

The Moran's I is mainly calculated by Eqs. (5) and (6). The spatial correlation is tested according to carbon emission distribution in different regions of the country. The Z score and p value respectively represent the spatial correlation coefficient and possibility of carbon emission in the whole life cycle of buildings. Table 2 shows the Moran's I values for the studied years.

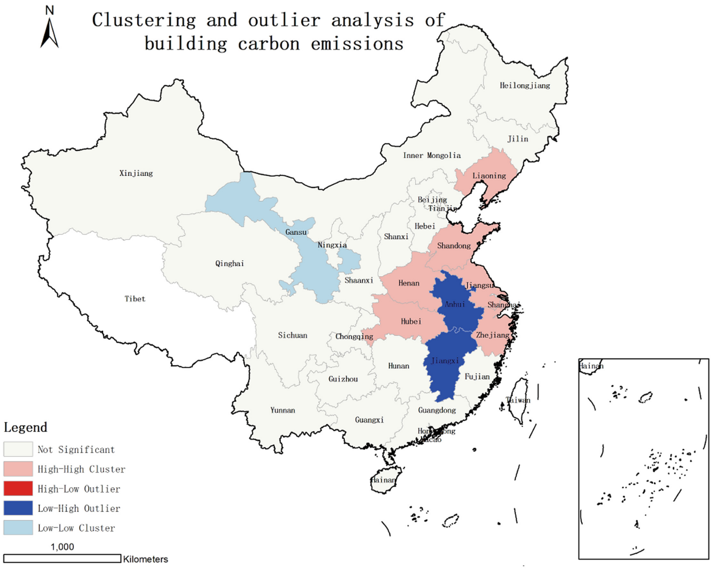
As Table 2 shows, the spatial correlation of building life cycle carbon emissions in 2010 and 2014 is relatively significant, while that in 2011 and 2012 is not. The spatial correlation of building life cycle carbon emissions in other years was significant. To improve the reliability of the results, carbon emission data of 2002, 2007, 2015 and 2020 are selected here for further analysis.

Figure 2 shows the results of clustering and outlier analysis in 2002 and 2020. The regional clustering results can be divided into high-high clustering (pink), high-low clustering (red), low-high clustering (blue) and low-low clustering (light blue).

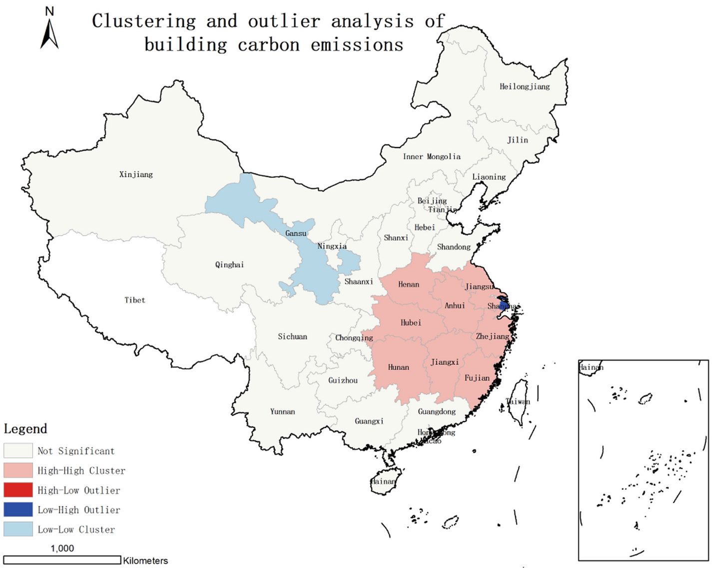
By comparing the carbon emission pattern in 2020, it can be found that the high clustering shifts from the eastern coastal areas to some coastal areas and central areas, indicating that the development center of the construction industry has shifted and the development of the construction industry in some coastal areas has slowed down. (2) The low clustering is still mainly in Gansu. It shows that the development level of the construction industry in Northwest China still does not exceed the national average level and is relatively lagging. (3) Shanghai has changed into a low and high clustering, which means that the speed of the construction industry in Shanghai has slowed down greatly. A comparison of economic development shows that in 2002, there was almost a positive correlation between economic development and the development level of the construction industry, which is one of the important driving forces of the economy, while in 2020, there was almost a decoupling between economic development and the development level of the construction industry.

Table 2. Building carbon emissions Moran's I value

Year	Moran's I	*Z* score	*p* value	Year	Moran's I	*Z* score	*p* value
2002	0.1427	2.3555	0.0199	2012	0.0537	1.1597	0.2534
2003	0.139	2.3026	0.0228	2013	0.1266	2.1396	0.0345
2004	0.1601	2.5855	0.0106	2014	0.1041	1.8348	0.07
2005	0.168	2.6739	0.0082	2015	0.1559	2.525	0.0125
2006	0.152	2.4751	0.0144	2016	0.1303	2.1918	0.0303
2007	0.1771	2.8059	0.0055	2017	0.17	2.707	0.0074
2008	0.1162	2.0065	0.0474	2018	0.1709	2.7143	0.0073
2009	0.155	2.5071	0.0132	2019	0.1622	2.5956	0.0103
2010	0.1095	1.8994	0.0606	2020	0.1762	2.7881	0.0058
2011	0.0799	1.5161	0.1347				



(a)



(b)

Fig. 2. Clustering results of building carbon emissions in China (a:2002; b:2020)

3.3 Identification of Driving Factors for Building Carbon Emissions

Identifying the main drivers of building carbon emissions can provide ideas for carbon reduction. In this paper, GTWR is used to evaluate the coefficient of carbon emission index in each region, in order to find the main sources of carbon emission growth.

Table 3. Driving coefficient of carbon emission factors

Item	2002	2007	2015	2020
ECP	3.0E+07	8.2E+07	6.8E+07	8.7E+07
EAP	1.5E+10	2.4E+10	2.1E+10	2.1E+10
ECI	3.2E+07	1.4E+08	2.5E+08	3.9E+08
OCP	1.3E+08	4.4E+08	7.4E+08	5.4E+08
OAP	5.4E+09	1.6E+10	2.3E+10	1.8E+10
OCI	3.8E+09	1.7E+10	3.2E+10	2.7E+10

As can been seen in Table 3, the multi-year emission coefficients of EAP, OCI and OAP are all in the top three, indicating that the construction scale, energy consumption level and building scale are the main driving factors for the carbon emission in the whole life cycle of a building. In addition, in 2015 and 2020, the coefficient of OCI surpassed that of EAP, meaning that operational phase carbon intensity began to become a key driver of building life-cycle carbon emissions. Therefore, if we want to control the carbon emission of the whole life cycle of buildings in the future, we should focus on controlling the energy consumption level, construction scale and building scale of operating buildings.

4 Conclusions

To discover the development trend of carbon emission related to buildings in China. A comprehensive measurement method of the whole life cycle carbon emission of the construction industry was put forward. Based on GTWR, the spatial-temporal development law of carbon emissions in China's construction industry is further analyzed, and the conclusions are as follows:

LCA and IPCC methods are combined to calculate the life-cycle carbon emissions of buildings. The results show that the life-cycle carbon emissions of the buildings reached the peak of 8.09×10^{12} kg in 2012. Furthermore, the carbon emission proportion of building materials production stage is the highest. The carbon emissions in the building's operation stage accounted for the second place. Transport and construction of building materials account for relatively low carbon emissions.

There is a spatial-temporal effect on carbon emissions in the whole life cycle of buildings. The results of GTWR coefficient showed that EAP, OCI and OAP were the main driving forces for the whole-life carbon emission of Chinese buildings, and the growth force of building carbon emission shifted from the materialization stage to the operation stage.

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