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Study on the Spatial and Temporal Evolution of Building Carbon Emissions and Influencing Factors in the Urban Agglomeration of the Yangtze River Economic Belt

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Abstract: With the rapid urbanization process, the construction industry has become a significant source of urban carbon emissions in China. The carbon emissions from buildings in the urban clusters of the Yangtze River Economic Belt, a crucial region for China's economic development, have attracted considerable attention. This study focuses on urban buildings and aims to investigate the primary influencing factors of building carbon emissions in the urban clusters of the Yangtze River Economic Belt. The study highlights the innovative use of nighttime light remote sensing data to analyze urban carbon emissions and provides an in-depth exploration of the spatiotemporal characteristics of building carbon emissions in the urban clusters of the Yangtze River Economic Belt. Utilizing nighttime light remote sensing data similar to DMSP-OLS and provincial-level building carbon emissions, combined with spatial autocorrelation and spatiotemporal geographically weighted regression models, the study estimates and analyzes the building carbon emissions from 2012 to 2021 in 71 prefecture-level and above administrative regions within the three major urban clusters of the Yangtze River Economic Belt. The results indicate a continuous increase in total building carbon emissions in the three major urban clusters of the Yangtze River Economic Belt, with an accelerating growth rate. Spatially, urban building carbon emissions exhibit enhanced convergence but decreasing correlation over time, demonstrating evolving spatiotemporal patterns. Furthermore, the study identifies economic development level, population size, built-up area, and industrial structure as the main factors influencing building carbon emissions, with industrial structure showing significant impact.

Keywords: Yangtze River Economic Belt urban agglomeration; building carbon emissions; DMSP-OLS-like nighttime lighting data; spatial and temporal evolution

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1. Introduction

According to the United Nations Environment Programme (UNEP) report, global carbon dioxide emissions reached the equivalent of 574 billion tons of carbon dioxide by the end of 2022, representing a 1.2% increase compared to 2021 [1]. The significant emissions of carbon dioxide and other greenhouse gases have intensified the greenhouse effect, leading to serious environmental issues [1]. As the world's largest developing country and the largest consumer of energy with the highest carbon emissions, China has proposed the dual carbon goals of peaking carbon emissions before 2030 and achieving carbon neutrality before 2060. With the introduction of the dual carbon goals, achieving them in a short period poses challenges for China, which operates under extensive production models and heavily relies on fossil fuels [2]. This also presents new challenges for industrial structure and energy transition.

According to the International Energy Agency (IEA), the operational phase of buildings consumed 30% of the global final energy consumption in 2021, with carbon emissions accounting for 27% of the total energy sector emissions [3]. The "China Building Energy Consumption and Carbon Emission Research Report (2022)" indicated that the carbon emissions from China's construction industry accounted for 50.9% of the country's total carbon emissions in 2020 [4]. The expansion of population size and economic development will lead to a continuous high demand for energy in the construction sector [5]. By 2050, the energy consumed in buildings is projected to increase by 46%-73% compared to 2019 levels [6]. This highlights the significant decarbonization potential of buildings, emphasizing the importance of accelerating energy efficiency and carbon reduction in the construction sector for achieving the dual carbon goals.

Currently, energy efficiency and carbon reduction in buildings face challenges including: (1) the increasing proportion of operational carbon emissions from buildings due to the rising urbanization and economic development, leading to higher urban density; (2) unclear understanding of the inherent interrelationships among factors such as population density, building density, and economic density [6]. Moreover, concerning the Yangtze River Economic Belt, the initial rapid urbanization has posed challenges for later energy efficiency due to the extensive building expansion.

This study, based on existing research, selected 71 cities at the prefectural level and above in the three major city clusters of the Yangtze River Economic Belt. By combining provincial-level building carbon emissions and nighttime light data, the study calculated the carbon emissions from urban buildings. Using spatial autocorrelation and spatiotemporal geographically weighted regression models, the study explored the spatiotemporal heterogeneity of factors influencing building carbon emissions in the city clusters of the Yangtze River Economic Belt, revealing their spatial distribution characteristics and dynamic evolution trends to provide macroscopic guidance for building energy efficiency.

2. Literature Review

Currently, research on building carbon emissions is primarily focused on estimation and influencing factors. In terms of estimating building carbon emissions, some studies concentrate on the use of the life cycle assessment (LCA) method [7,8], which divides the building's life cycle into four stages and calculates the carbon emissions of the building at each stage [9–11]. Other researchers utilize methods such as input-output analysis [12], emission factor approach [13], on-site measurements [14], and other approaches to quantify building carbon emissions. However, the challenging nature of obtaining the required data for these methods, along with issues related to data availability and timeliness, often restrict the research scope to the national, provincial, or individual building levels.

Supported by remote sensing technology, nighttime light data, as one of the accessible public datasets, provides a visual representation of societal development and human activities [15]. It is also one of the most direct spatial characteristics of human social urbanization and is widely used for estimating regional economic activities [16], energy production activities [17], electricity consumption [18], and population [19] among others. In studies estimating carbon emissions using nighttime light data, analyses from a spatiotemporal perspective are often conducted using DMSP-OLS data and NPP-VIIRS data. Wang et al. [20] utilized DMSP/OLS-NPP/VIIRS nighttime light data from 2000 to 2019 to develop a model for estimating transportation carbon emissions, analyzing the spatiotemporal evolution characteristics of transportation carbon emissions in 30 provinces and some counties in China. For regional carbon emissions, Zheng et al. [21] combined DMSP/OLS and NPP/VIIRS nighttime light data to construct a carbon emission estimation model, assessing the carbon emissions at the city, county, and town levels in Fujian Province from 2000 to 2020.

In studying the influencing factors on carbon emissions, researchers primarily employ methods such as the Log-Mean Divisia Index (LMDI) [22], IPAT, Kaya, and STIRPAT models to analyze from multiple perspectives including economic development level, population, technology, urbanization level [23], among others. Lu et al. [24] evaluate the impact of promoting new energy vehicles on urban decarbonization from the perspective of urban transportation. Li et al. [25] utilized the Kaya identity and LMDI method to construct a carbon emissions model for the operational phase of commercial buildings, revealing a negative correlation between the building area demand per unit GDP and population density with carbon intensity. Zhang et al. [26] found, based on the LEAP model, that the contribution rate of building energy efficiency upgrades and renewable energy applications to carbon emissions reduction in public buildings is 53.12%. Huo et al. [27] combined the STIRPAT model with the least squares method to investigate the impact mechanism of the main driving factors affecting building carbon emissions across building sub-industries.

In recent years, many scholars have conducted research on the spatiotemporal characteristics of carbon emissions in China at different scales. The research findings indicate that there are significant spatial transmission characteristics among provinces in China [28], with high carbon emission regions primarily concentrated in economically developed areas such as the eastern coastal regions [29]. In the Yellow River Basin, the total carbon emissions from energy consumption have been steadily increasing, while the growth rate is gradually declining [30], highlighting the increasing prominence of carbon imbalance [31]. Cities in the Yangtze River Economic Belt exhibit significant positive spatial correlation and agglomeration in carbon emissions [32]. However, the overall carbon emission efficiency is not high, showing a trend of fluctuating changes [33]. Regarding the factors influencing carbon emissions, most studies consider the level of economic development [34], industrial structure [35], population size [36], and land use [37] to be important factors affecting carbon emissions.

In conclusion, the existing literature lacks comprehensive research on the macro-level analysis of carbon emissions from buildings and their spatiotemporal evolution. Additionally, studies on carbon emissions in Chinese river basins have mainly focused on the Yellow River Basin, overlooking the Yangtze River Basin, a significant economic development region in China. Investigating the carbon emissions from buildings in the Yangtze River Basin can aid in establishing emission reduction demonstration zones and innovative emission reduction models. This study contributes by (1) specifically examining the spatiotemporal evolution of building carbon emissions in urban clusters in the Yangtze River Economic Belt and evaluating the influence of economic, population, and urbanization factors on building carbon emissions; (2) utilizing DMSP-OLS nighttime light data and integrating DMSP-OLS and SNPP-VIIRS to enhance the accuracy of estimating building carbon emissions in urban clusters.

3. Study Area, Materials and Methods

3.1. Study Area

The Yangtze River Economic Belt traverses the eastern, central, and western regions of China and is a key component of the country's strategic initiatives. It is recognized as an inland economic belt with significant global influence, a platform for collaborative development and exchanges between the eastern, central, and western regions, a gateway for integrated development along the coastal, riverside, and border areas, and a leading demonstration zone for ecological civilization. With its population and GDP collectively exceeding 40% of the national total, the Yangtze River Economic Belt holds strategic importance. This study focuses on the urban clusters within the Yangtze River Economic Belt, including the Yangtze River Delta, middle reaches, and Chengdu-Chongqing urban clusters, covering 71 prefecture-level administrative regions across 9 provinces and municipalities (Shanghai, Chongqing, Jiangsu, Zhejiang, Anhui, Hubei, Hunan, Jiangxi, and Sichuan).

3.2. Research Methodology

3.2.1. Calculation of Building Carbon Emissions

In this study, the carbon emissions of provincial-level buildings were estimated using the carbon emission factors of various types of energy determined by the IPCC. The energy consumption and carbon emissions during the operational phase of buildings mainly stem from daily activities such as electricity supply, heating, and cooling [6,38–40]. By multiplying the statistical data on electricity and natural gas consumption in different regions by the corresponding carbon emission factors [41] (Tables 1 and 2), the carbon emissions were calculated.

$$CE_{ip} = E_{ip} \times k_{pe} + N_{ip} \times LVP_n \times k_n \times COF_n \times \frac{44}{12} \tag{1}$$

where CE_{ip} denotes the building carbon emissions of province p in year i; E_{ip} denotes the electricity consumption of province p in year i; k_{pe} denotes the carbon emission factor of electricity in province p; N_{ip} denotes the natural gas consumption of province p in year i; LVP_n denotes the low-level heat generation of natural gas; k_n denotes the carbon emission factor of natural gas; COF_n denotes the oxidation efficiency of natural gas.

Table 1. Low-level heat production and emission factors for natural gas.

Typology	LCV (PJ/10 m83)	EF (tC/GJ)	COF (%)
petroleum	3.89	0.0153	99

Table 2. Carbon Emission Factors for Electricity in the Yangtze River Economic Belt City Cluster Provinces.

Provinces	Electricity Carbon Emission Factor (kgCO$_2$/kWh)
Shanghai	0.583
Jiangsu Province	0.645
Zhejiang Province	0.542
Anhui	0.708
Hubei Province	0.367
Hunan	0.514
Jiangxi	0.584
Chongqing	0.474
Sichuan Province	0.126

Drawing on the principle of total allocation [31], this study calculates the carbon emissions from building activities in prefecture-level administrative regions of the Yangtze River Economic Belt by leveraging the ratio of provincial-level nighttime light data to prefecture-level nighttime light data. The formula is expressed as follows:

$$CE_{ijp} = TDN_{ijp} \times \frac{CE_{ip}}{TDN_{ip}} \tag{2}$$

where CE_{ijp} denotes the building carbon emissions in city j of province p in period i; TDN_{ijp} denotes the total value of night light in city j of province p in period i; CE_{ip} denotes the carbon emission from buildings in province p in period i; TDN_{ip} denotes the total value of nighttime lights in province p in period i.

3.2.2. Spatial Autocorrelation Analysis

This study employed Global Moran's I to examine the spatial correlation and clustering of carbon emissions from building activities in urban clusters within the Yangtze River Economic Belt. Global Moran's I ranges from −1 to 1, with values above 0 indicating significant positive spatial correlation and values below 0 indicating negative correlation. The formula for computing Global Moran's I is presented as follows [42]:

$$\mathrm{I} = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}(x_i - \overline{x})(x_j - \overline{x})}{\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}\sum_{i=1}^{n}(x_i - \overline{x})^2} \tag{3}$$

where n denotes the number of administrative units at the prefecture level; x_i, x_j denote the carbon emissions from buildings in an administrative unit; $\overline{x}$ denotes the average value of building carbon emissions in an administrative unit; W_{ij} denotes the spatial weight matrix between administrative units i, j.

The LISA cluster test was employed to conduct local spatial autocorrelation analysis, aiming to investigate the local similarity and dissimilarity of spatial relationships in building carbon emissions among adjacent administrative units.

$$I_i = \frac{n(x_i - \overline{x})\sum\limits_{j=1}^{n} W_{ij}(x_j - \overline{x})}{\sum\limits_{i=1}^{n} (x_i - \overline{x})^2} \tag{4}$$

When $I_i > 0$, it indicates a spatial clustering distribution in adjacent areas, typically showing as H-H or L-L, representing high-high or low-low clustering of building carbon emissions in neighboring regions. Conversely, when $I_i < 0$, it indicates a spatial dispersion distribution in adjacent areas, manifesting as H-L or L-H, representing situations where high (low) areas or low (high) areas are surrounded by neighboring regions.

3.2.3. The Geographically and Temporally Weighted Regression (GTWR) Model

Expanding upon the Geographically Weighted Regression (GWR) model, the GTWR model incorporates a temporal dimension through the use of non-stationary spatiotemporal weight matrices. This advancement addresses the limitation of GWR, which primarily focuses on spatial effects while overlooking temporal influences. In this study, the GTWR model was employed to investigate the spatiotemporal evolution of carbon emissions from building activities in urban clusters of the Yangtze River Economic Belt, uncovering the spatial heterogeneity characteristics of various driving factors. The formula is provided below [43].

$$Y_i = \beta_0(\mu_i, v_i, t_i) + \sum_{j=1}^{k} \beta_i(\mu_i, v_i, t_i)x_{ij} + \varepsilon_i \tag{5}$$

where Y_i is the building carbon emissions of the i-th administrative region; $(\mu_i,\ v_i,\ t_i)$ is the spatio-temporal coordinates of the i-th administrative region in longitude, dimension, and point in time; $\beta_0(\mu_i,\ v_i,\ t_i)$ is the regression intercept term; $\beta_i(\mu_i,\ v_i,\ t_i)$ is the regression coefficient; x_{ij} is the value of the jth independent variable in the ith administrative region; ε_i is the residual.

3.3. Data Sources

3.3.1. Night Lighting Data

Compared to other nighttime light datasets, the DMSP-OLS and NPP-VIIRS nighttime light data offer advantages such as long-term dynamic archives, extensive coverage, and open data sources. In this study, the "DMSP-OLS-like China nighttime light remote sensing dataset" [44] was utilized. The DMSP-OLS data were calibrated using the "pseudo-invariant pixel" method. Considering the temporal resolution consistency between DMSP-OLS and SNPP-VIIRS data, missing data in the original monthly SNPP-VIIRS dataset were rectified before synthesizing annual SNPP-VIIRS data, which were then further transformed into DMSP-OLS-like data.

3.3.2. Statistical Data

The energy consumption data were extracted from the provincial energy inventories within the Chinese Carbon Accounting Database (CEADs) for the period spanning from 2012 to 2021 [45–49]. Information regarding the GDP, population size, built-up area, and industrial structure of the provinces and city clusters situated in the Yangtze River Economic Belt was sourced from the Big Data Platform of the Yangtze River Economic Belt. Statistical yearbooks and bulletins from the years 2012 to 2021 across various regions were consulted for data compilation. The year-end population figures were utilized to assess population size, while the ratio of value added by the tertiary industry to GDP was employed for evaluating the industrial structure.

4. Analysis of Results

4.1. Carbon Emissions from Buildings in Urban Agglomerations

According to Figure 1, the building carbon emissions in the Yangtze River Economic Belt exhibited a consistent upward trend from 2012 to 2021, with an increasing growth rate. Specifically, the building carbon emissions in the Chengdu-Chongqing city cluster in the upper reaches increased from 1.02 billion tons in 2012 to 1.80 billion tons in 2021. In the middle reaches of the Yangtze River, the building carbon emissions grew from 1.92 billion tons in 2012 to 3.23 billion tons in 2021. Similarly, the Yangtze River Delta city cluster saw an increase in building carbon emissions from 6.42 billion tons in 2012 to 10.97 billion tons in 2021. The building carbon emissions in the Yangtze River Economic Belt city clusters are characterized by varying proportions. The Yangtze River Delta city cluster exhibits the highest proportion, averaging 69.35%. Following closely is the middle reaches of the Yangtze River city cluster, with an average proportion of 19.93%. In contrast, the Chengdu-Chongqing city cluster has the smallest proportion of building carbon emissions, averaging 10.72%. Overall, the building carbon emissions in the city clusters of the Yangtze River Economic Belt have shown stable trends. While the proportion of building carbon emissions in the Chengdu-Chongqing city cluster is on the rise, there is a slight decrease in the proportions for the Yangtze River Delta city cluster and the middle reaches of the Yangtze River city cluster.

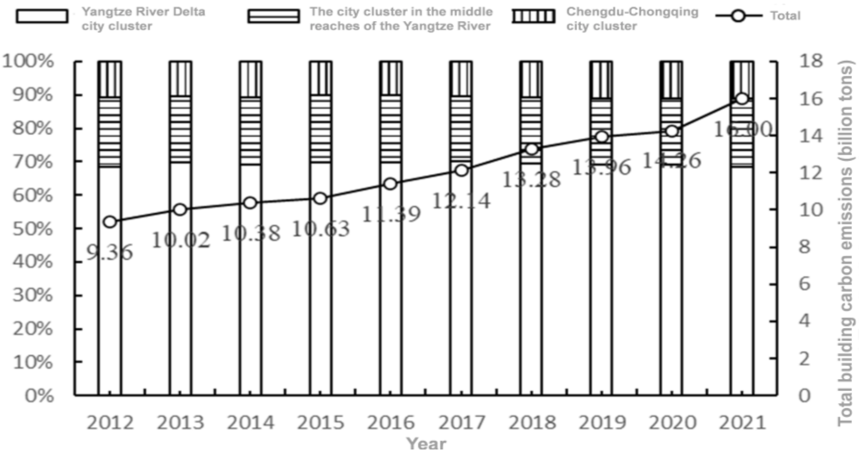


Figure 1. Trends in carbon emissions from buildings in the Yangtze River Economic Belt city cluster, 2012–2021.

4.2. Global Spatial Autocorrelation Analysis

During the period from 2012 to 2021, the building carbon emissions in the city clusters of the Yangtze River Economic Belt exhibited a consistent positive spatial autocorrelation, as indicated by the global Moran's I index (Table 3). The average global Moran's I index over the decade was calculated as 0.3559, with all associated p-values being statistically significant at the 0.01 level based on significance testing. This statistical analysis suggests a significant positive relationship in the spatial distribution of building carbon emissions among the city clusters, highlighting a tendency for cities with higher emissions to be located in proximity to those with lower emissions.

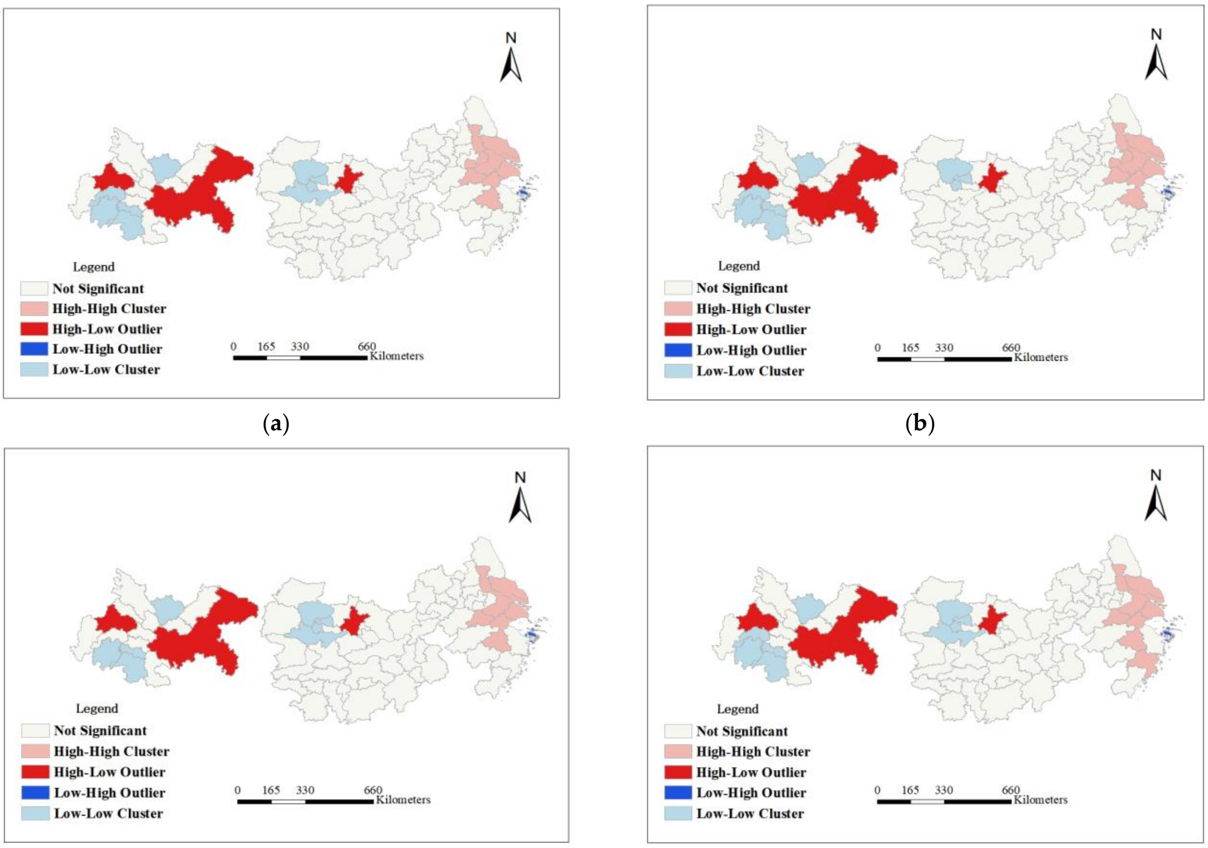
Furthermore, the trend in the global Moran's I index showed an upward trajectory from 2012 to 2018, signifying an increasing spatial homogeneity in building carbon emissions across the city clusters during that period. However, from 2018 to 2021, the global Moran's I index exhibited a fluctuating downward trend, indicating a weakening spatial correlation in building carbon emissions post-2018. This evolution in spatial patterns suggests a shift in the spatial distribution dynamics of building carbon emissions within the city clusters of the Yangtze River Economic Belt.

Table 3. Global Moran's I.

	2012	**2013**	**2014**	**2015**	**2016**
Moran's I	0.33	0.35	0.34	0.35	0.36
P	0.00	0.00	0.00	0.00	0.00
Z	4.80	5.05	4.93	5.00	5.10
	2017	**2018**	**2019**	**2020**	**2021**
Moran's I	0.37	0.38	0.36	0.37	0.36
P	0.00	0.00	0.00	0.00	0.00
Z	5.35	5.33	5.07	5.21	5.06

4.3. Local Spatial Autocorrelation Analysis

In the years 2012, 2015, 2018, and 2021, around 28.77%, 27.4%, 26.03%, and 28.77% of cities, respectively, exhibited notable clustering tendencies. As is shown in Figure 2, in Lisa's Aggregation Chart, HH-type cities were predominantly concentrated within the Yangtze River Delta city cluster, while LL-type cities were primarily distributed in the upstream and midstream city clusters along the Yangtze River. Over the period from 2012 to 2021, HH-type cities in the Yangtze River Delta gradually shifted southward.



(**a**) (**b**)

(**c**) (**d**)

Figure 2. Lisa's Aggregation Chart. (**a**–**d**) represent the distribution of spatial and temporal changes of local spatial autocorrelation analysis in the Yangtze River Economic Belt in 2012, 2015, 2018, and 2021, respectively.

During the same period, LL-type cities were mainly situated in the upstream and midstream city clusters of the Yangtze River, located in the less developed inland regions of central and western China with lower population density, resulting in reduced levels of building carbon emissions. HL-type cities from 2012 to 2021 were mainly the three central cities in the upstream and midstream regions of the Yangtze River, namely Wuhan, Chongqing, and Chengdu. Chengdu and Chongqing served as economic, financial, and technological hubs in the upper reaches of the Yangtze River, while Wuhan acted as a pivotal city in the midstream, attracting a significant population.

Moreover, in 2016 and 2019, Changsha was classified as an HL-type city. The only LH-type city during the period from 2012 to 2021 was Zhoushan, located in Zhejiang Province. Zhoushan's unique island-based topography led to its population accounting for only about 1% of the total population of Zhejiang Province in 2021. With a built-up area covering 2% of the province's total built-up area, Zhoushan exhibited relatively low levels of building carbon emissions, maintaining this classification consistently from 2012 to 2021.

4.4. Analysis of Spatial Heterogeneity of Impact Factors

By visualizing the regression coefficients of various factors for the years 2012, 2015, 2018, and 2021 based on the GTWR model's local estimation results (Table 4), significant spatial heterogeneity in building carbon emissions within the city cluster of the Yangtze River Economic Belt can be observed (Figures 3–6).

Table 4. The result of GTWR model.

Variable	Min	Max	Average
GDP	−0.0975	0.4663	0.1962
PPS	0.0701	2.7124	1.0347
ABD	−4.5221	4.6414	−0.6410
IS	−43.8568	29.3992	1.4063
R^2		0.971	
R^2 Adjusted		0.971	
AICc		10,179.4	

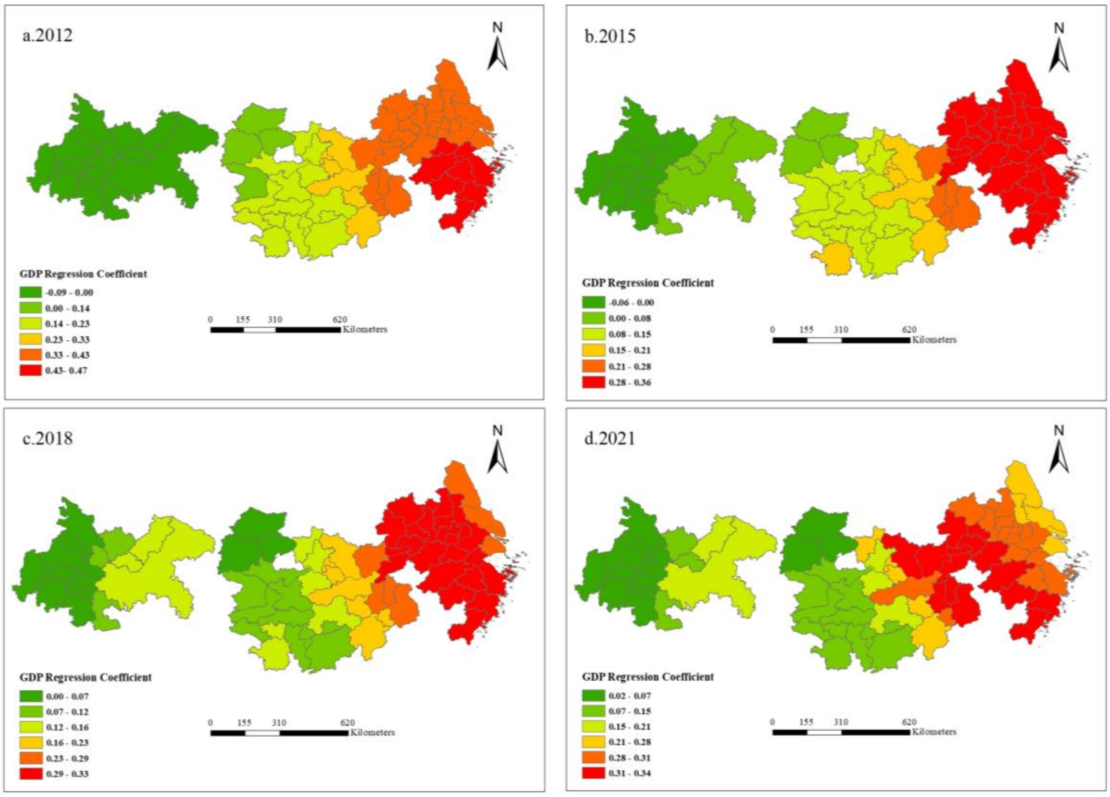


Figure 3. Spatial distribution of regression coefficients: GDP.

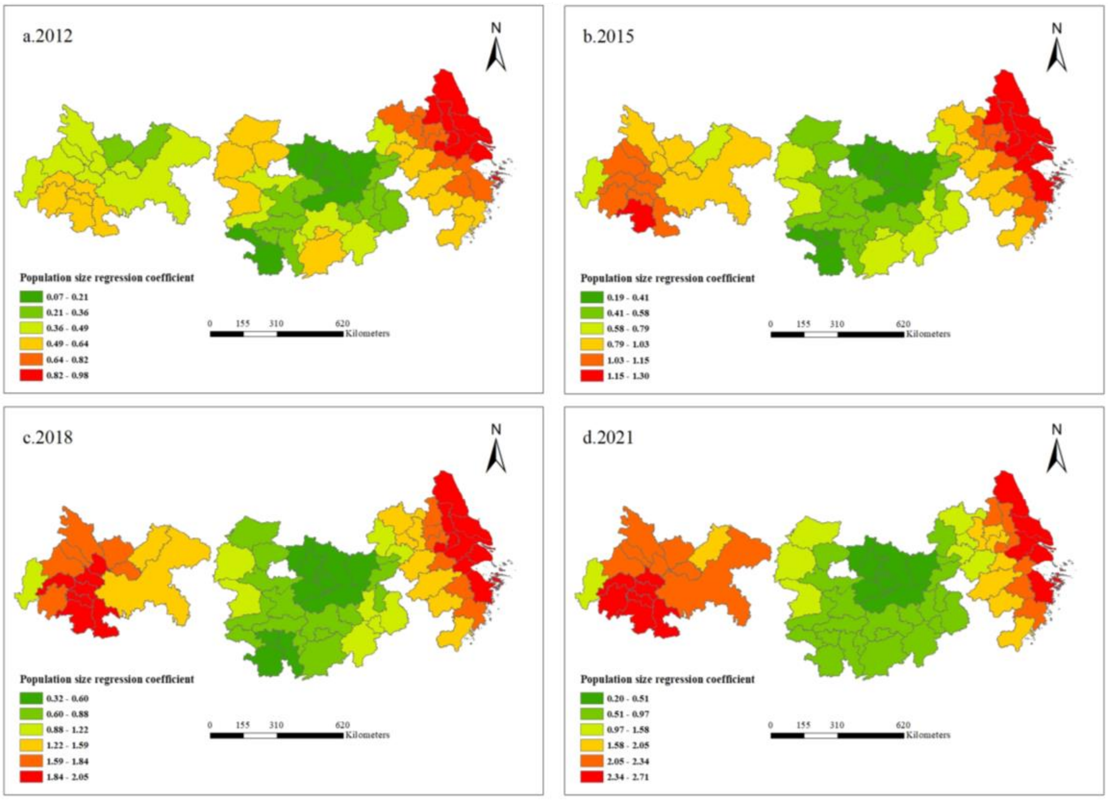


Figure 4. Spatial distribution of regression coefficients: Population.

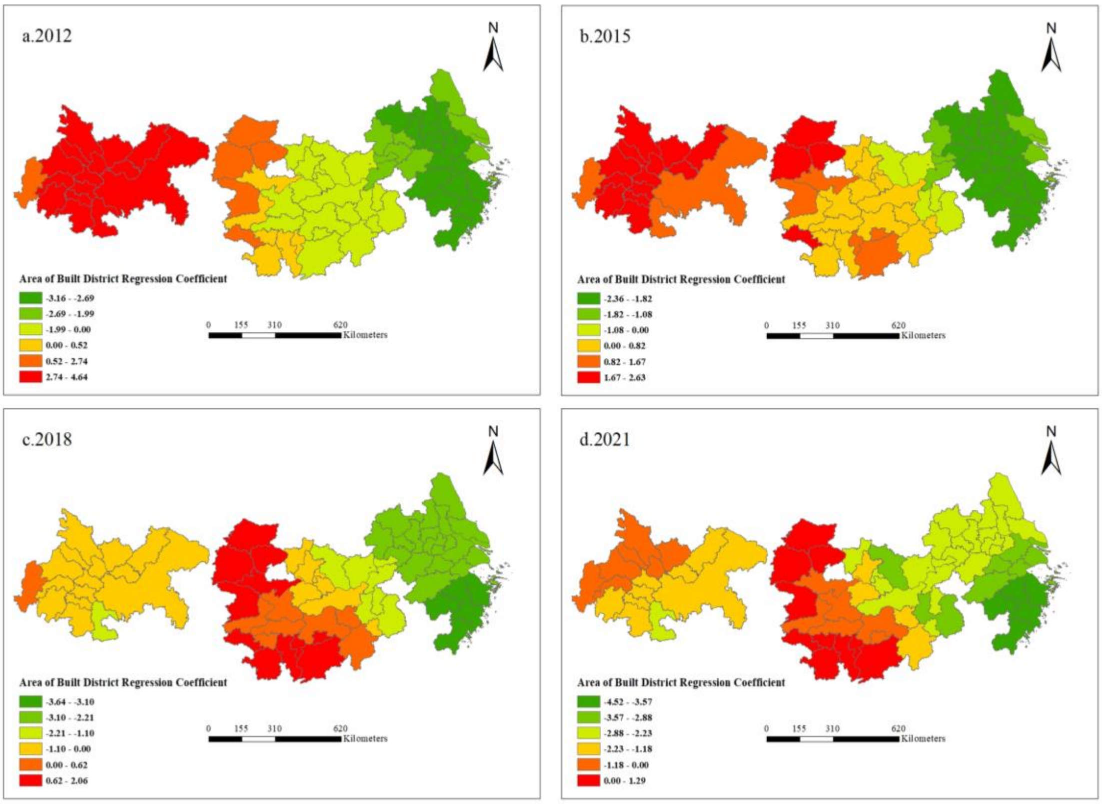


Figure 5. Spatial distribution of regression coefficients: Industrial Structure.

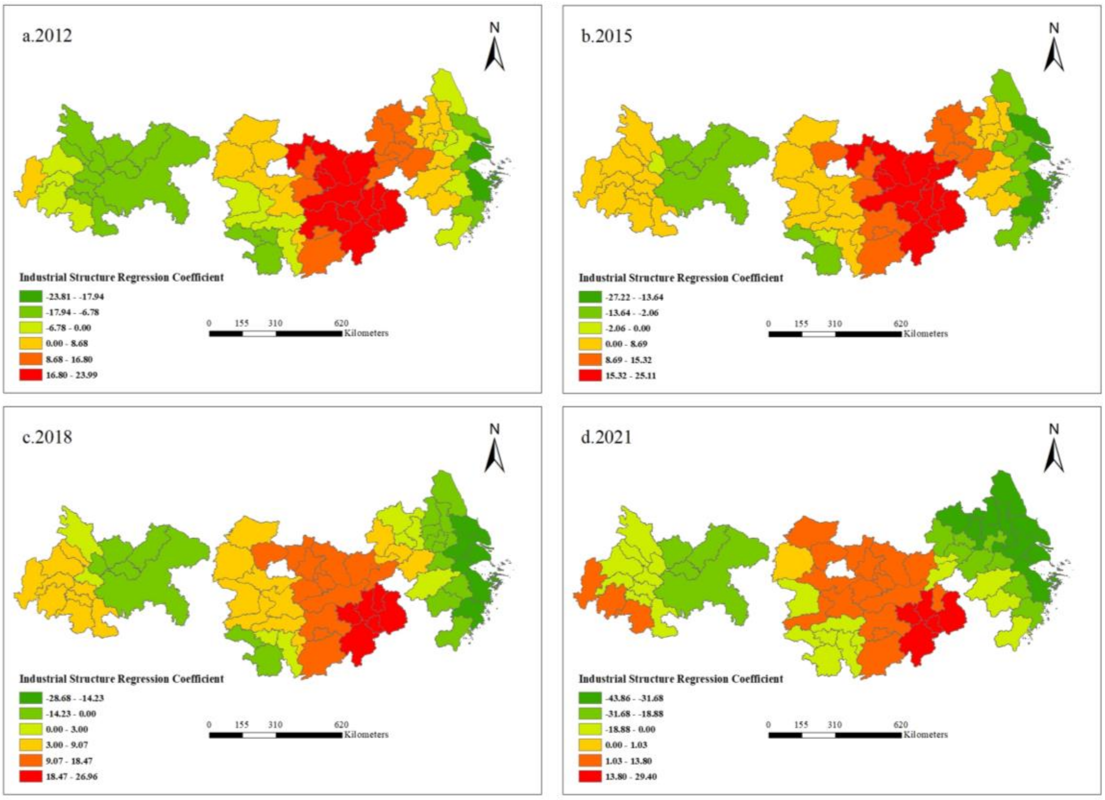


Figure 6. Spatial distribution of regression coefficients: Area of Built District.

1. GDP demonstrates a positive driving effect on building carbon emissions in most regions, indicating that higher levels of economic development lead to increased building carbon emissions. Specifically, within the city cluster of the Yangtze River Delta, building carbon emissions are most significantly influenced by GDP, followed by the midstream city cluster of the Yangtze River, with the Chengdu-Chongqing city cluster exhibiting the lowest impact. Over time, the influence of economic levels on building carbon emissions has shifted gradually from being high in the eastern regions to being high in the central regions. Conversely, the negative driving force is primarily concentrated in the western part of the Chengdu-Chongqing city cluster, where higher economic levels correspond to lower levels of building carbon emissions.

2. The expansion of population size has driven an escalation in urban building carbon emissions, as evidenced by the positive regression coefficients for population size across all spatiotemporal units in the GTWR regression analysis. Before 2014, significant values were predominantly observed in the Eastern coastal city of the Yangtze River Delta city cluster, and due to the small population of the West, most of its urban population has little impact on carbon emissions. Whereas post-2014, the influence of population size on building carbon emissions in the Chengdu-Chongqing city cluster has progressively intensified. Previously less impacted places in the west, such as Chongqing Nanchong, etc., have seen a significant increase in impacts. Although the Chengdu-Chongqing city cluster is relatively backward in terms of economic development. With the promotion of the Western Development Policy, the government has attracted investments with lower land prices, which has led to the development of industries in the region. It has also prompted a return of population and led directly to an increase in building carbon emissions.

3. Examining the relationship from the perspective of built-up area, in 2012, the central and eastern cities of the midstream city cluster along the Yangtze River, as well as the Yangtze River Delta city cluster, displayed a negative correlation between built-up area and building carbon emissions. By 2015, only Shangrao, Jingdezhen, and Huanggang in the midstream city cluster along the Yangtze River maintained a negative association with built-

up area. Following 2015, this negative correlation expanded toward the western regions. By 2021, apart from select cities in the northwest and southwest of the midstream city cluster along the Yangtze River, the majority of cities exhibited a significant negative correlation between built-up area and building carbon emissions. This result contradicts our common knowledge, as typically building carbon emissions increase with the expansion of built-up area. However, it is not impossible for a negative correlation between built-up area and building carbon emissions to occur. With the rapid urban expansion, the urban green space area is significantly increasing, leading to an increase in carbon sinks [50]. Along with the cooling effect of green spaces, electricity consumption in urban areas has decreased [51], and the renovation of old cities and energy-saving improvements in buildings have greatly alleviated the ecological pressures in urban centers [52]. This pattern highlights the high-quality progression of urbanization levels across the entirety of the city cluster within the Yangtze River Economic Belt.

4. Among the selected factors influencing building carbon emissions in the city clusters of the Yangtze River Economic Belt, the impact of industrial structure emerges as the most prominent and continues to deepen over time. The influence of industrial structure in the Yangtze River Delta city cluster diminishes from east to west, while in the central and western city clusters, it transitions from positive correlation to negative correlation. The midstream city cluster along the Yangtze River predominantly shows a positive correlation, with the strong positive correlation of industrial structure to building carbon emissions primarily concentrated in Jiangxi Province. In the eastern part of the Chengdu-Chongqing city cluster, the correlation is mainly negative, while some western cities exhibit a positive correlation. This underscores the effectiveness of the transition toward a low-carbon industrial structure.

5. Conclusions

5.1. Conclusions

This study utilized class DMSP-OLS nighttime light data from 2012 to 2021 in the city clusters of the Yangtze River Economic Belt. Based on the total allocation approach and provincial-level data, the building carbon emissions of prefecture-level cities were calculated. Spatial autocorrelation analysis and the GTWR model were employed to investigate the spatiotemporal evolution trends and associated influencing factors of building carbon emissions in the three major city clusters of the Yangtze River Economic Belt. The key findings are summarized as follows:

1. Between 2012 and 2021, the building carbon emissions in the three major city clusters of the Yangtze River Economic Belt exhibited a consistent upward trend in total volume, accompanied by a progressively accelerating growth rate. Over this period, the total building carbon emissions surged from 9.36 billion tons in 2012 to 16 billion tons in 2021, with the growth rate spiking from 21.71% in the 2012-2016 period to 40.39% in the 2016-2021 period. The building carbon emissions in the three major city clusters exhibited a geographical distribution pattern of the Yangtze River Delta city cluster > the midstream city cluster along the Yangtze River > the Chengdu-Chongqing city cluster, with average proportions of 69.35%, 19.93%, and 10.72%, respectively.

2. During the period from 2012 to 2021, the Moran's I index for building carbon emissions in the three major city clusters of the Yangtze River Economic Belt remained positive. From 2012 to 2018, there was a gradual strengthening of spatial autocorrelation in building carbon emissions within the city clusters of the Yangtze River Economic Belt. However, starting from 2018, the spatial correlation of urban building carbon emissions began to gradually weaken. The areas with high-high (HH) clustering were predominantly concentrated in the Yangtze River Delta city cluster, while the low-low (LL) clustering areas were primarily found in the midstream city cluster along the Yangtze River and the Chengdu-Chongqing city cluster. Over time, the HH clustering areas extended gradually southward.

3. The building carbon emissions in the city clusters of the Yangtze River Economic Belt exhibit significant spatiotemporal heterogeneity, influenced by a multitude of factors.

The impact of economic development on building carbon emissions gradually diminishes from east to west. Population size plays a positive driving role in building carbon emissions, with higher values predominantly observed in the Chengdu-Chongqing and Yangtze River Delta city clusters. The built-up area shows a negative correlation with building carbon emissions in most cities. The industrial structure has the most significant influence on building carbon emissions, leading to a transition from positive to negative correlations as industries shift toward low-carbonization. Higher negative correlation values are mainly found in the eastern cities of the Yangtze River Delta city cluster, while strong positive correlations are concentrated in Jiangxi Province.

5.2. Policies

Firstly, given the Yangtze River Economic Belt as a coordinated development zone for interaction and cooperation between the eastern, central, and western regions, the reduction of building carbon emissions should not focus solely on individual cities or city clusters. Instead, it is necessary to break through administrative boundaries, coordinate comprehensively, and collaborate to establish a carbon trading and offset system.

Secondly, as the economic level develops, the population flows toward the central cities of each city cluster, intensifying the pressure for building carbon emissions reduction in these central cities. The building carbon emissions in central cities remain a key focus for the future, especially in the midstream cities of the Yangtze River and the Chengdu-Chongqing city clusters. To alleviate the pressure of building emission reduction in central cities, optimizing the urban development structure and industrial layout in central cities and surrounding areas to promote population inflows is essential.

Finally, industrial structure and built-up area are the main factors influencing building carbon emissions. It is essential to actively promote the development of energy-efficient and high-quality industries. In regions with higher economic development levels, accelerating the development of green technologies is crucial to facilitate the transition toward greener industries and improve land-use efficiency in built-up areas. In areas with relatively lower economic development levels, adhering to the concept that “green mountains and clear water are as valuable as mountains of gold and silver”, proper planning of urban and natural areas and strict control over industrial access thresholds are necessary.

5.3. Limitations and Future Prospects

The Yangtze River Economic Belt, being one of China’s key economic development zones spanning the eastern, central, and western regions, has attracted considerable attention from the academic community regarding environmental issues. This study primarily investigates the spatiotemporal evolution of building carbon emissions in the three major urban clusters within the Yangtze River Basin, but it also has the following limitations.

(1) This study only considered electricity and natural gas as energy sources in calculating the energy consumption during the operational phase of buildings, which may result in some errors in estimating the provincial-level building carbon emissions. In the future, multiple energy sources could be introduced for analysis, and a more comprehensive dataset could be utilized to assess carbon emissions. (2) Building carbon emissions are influenced by multiple factors, not limited to the GDP, population size, built-up area, and industrial structure discussed in this paper. Future research could consider integrating technological level and urban planning for a comprehensive analysis. (3) Finally, this study focused solely on the carbon emissions of buildings during the operational phase, neglecting emissions from other stages. Carbon emissions are generated throughout the entire life cycle of a building, from material production, planning and design, construction and transportation, operation and maintenance, to dismantling and disposal. Therefore, investigating the carbon emissions of the entire building life cycle is necessary and poses a significant challenge.

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