A STUDY OF THE SPATIAL HETEROGENEITY OF CARBON EMISSIONS AND THE INFLUENCING FACTORS OF CONSTRUCTION LAND IN THE YANGTZE RIVER ECONOMIC BELT

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(Received 22nd Sep 2024; accepted 23rd Dec 2024)

Abstract. The objective of this study is to examine the disparities in the carbon emission consequences of construction land in the Yangtze River Economic Belt. A time series analysis of the characteristics of carbon emissions from construction land in the Yangtze River Economic Zone was presented, based on data from 2009 to 2021. The spatial autocorrelation, standard deviation ellipse and center of gravity migration were employed to analyze the spatial distribution pattern of carbon emissions and migration characteristics of the changes. The Tyrell's index was used to reflect the process of changes of intra- and inter-regional differences in carbon emissions. Geographically weighted regression model was employed to explore the impact of spatial differences in carbon emissions. The findings of the study indicated that: (1) The growth rate of total carbon emissions from construction land in the Yangtze River Economic Belt was 14.16%, while the growth rates of total carbon emissions in the upstream, midstream and downstream regions were 0.20%, 17.17% and 22.66%, respectively. There was a decreasing trend in the intensity of carbon emissions from east to west, with the overall difference between regions slowly decreasing. However, there was an increasing trend in the inter-regional difference and a decreasing trend in the intra-regional difference. (2) Both total carbon emissions and intensity demonstrated a downstream > midstream > upstream pattern, exhibiting a notable and consistent positive spatial agglomeration. The elevated levels of carbon emission hotspots were concentrated in the downstream sector, while the lower values were situated in the upstream region. The center of gravity of carbon emissions was located in Hubei Province and exhibited a westward migration over the 12 years, with a longitudinal shift of 0.55° and a latitudinal shift of 0.07°. However, the spatial evolution in the northeast-southwest direction displayed a relatively high degree of instability. (3) There was a positive correlation between the resident population, industrial structure, energy consumption and carbon emissions, with the most significant influence observed in the Jiangsu, Zhejiang and Shanghai regions. The correlation between the upstream construction land and carbon emissions had undergone a notable change, initially becoming negative and subsequently positive. This shift had resulted in an enhanced influence of construction land in the middle reaches, while that in the lower reaches had experienced a reduction in impact. The downstream region should prioritize industrial ecologization, while the upstream should focus on eco-industrialization to enhance service value of ecological resources.
Keywords: *carbon emissions, spatial auto-correlation, Tyrell's index, standard deviational ellipse, geographically weighted regression*

Introduction

The mitigation of global warming has become a significant challenge for humanity, with the IPCC emphasizing the necessity for global action to prevent the occurrence of extreme hazards. To this end, it is imperative that global warming is limited to 1.5°C in order to avoid the most severe consequences (Houghton and Hackler, 1999). It is estimated that, driven by industrialization and urbanization, global CO_2 emissions caused by land use account for approximately 1/3 of the total carbon emissions from human activities, with the contribution of land use to the greenhouse effect estimated to be approximately 24% (Goldewijk and Ramankutty, 2004). As the world's largest emitter of carbon dioxide, China is projected to produce 11.102 billion tons of CO_2 in 2021, representing 31.56% of the global total. China's high carbon emissions have attracted considerable attention from countries around the globe. This has resulted in significant international pressure on China, as well as creating obstacles to its economic development.

In terms of research content, scholars have assessed and calculated the levels of carbon emissions from agriculture (Qin et al., 2022; Huang et al., 2019; Tian et al., 2014; Yigen and Kaiwen, 2019; Yan et al., 2023; Zou et al., 2022), industry (Fan et al., 2015; Guo et al., 2021; Aslam et al., 2021; Li et al., 2018; Wang et al., 2020), mining (Shao et al., 2016) and energy (Zhang et al., 2009). They have also analyzed the links between carbon emissions and economic growth (Narayan and Narayan, 2010; Chang, 2010; Mirza and Kanwal, 2017; Gozgor et al., 2018; Aslam et al., 2021; Li et al., 2018) and between carbon emissions and energy consumption (Zhang et al., 2009; Narayan and Narayan, 2010; Chang, 2010; Mirza and Kanwal, 2017). In terms of research scale, studies have been carried out at the national (Qin et al., 2022; Huang et al., 2019; Tian et al., 2014; Yan et al., 2023; Guo et al., 2021; Aslam et al., 2021; Zhang et al., 2009; Narayan and Narayan, 2010; Chang, 2010; Mirza and Kanwal, 2017; Gozgor et al., 2018; Meng et al., 2011; Nie and Lee, 2023), regional (Li et al., 2018; Wang et al., 2020; de Araújo et al., 2009; Ali and Nitivattananon, 2012) or urban (Shao et al., 2016) level. At present, there is a dearth of studies that have taken the Yangtze River Economic Belt as a research object to investigate its carbon emissions and the spatial heterogeneity of influencing factors.

The Yangtze River Economic Belt, which encompasses the three major regions of the East, the Middle East and the West, and connects the "One Belt, One Road" initiative, is one of China's most economically active, open and densely populated regions. It is characterized by contradictory interactions between an upward economic trend and a downward ecological trend, and plays an important strategic role in China's overall national economic development. On 25 March 2016, China considered and adopted "the Outline of the Plan for the Development of the Yangtze River Economic Belt," which identifies the promotion of the development of the Yangtze River Economic Belt as a major strategy related to the overall situation of national development. Since General Secretary Xi Jinping convened a symposium on promoting the development of the Yangtze River Economic Belt in Chongqing in January 2016, he has repeatedly emphasized the necessity of prioritizing ecological considerations and pursuing green development in order to facilitate the advancement of the Yangtze River Economic Belt. This entails a commitment to safeguarding the environment, avoiding large-scale development, and collectively striving to transform the Yangtze River Economic Belt into a prosperous and environmentally sustainable economic zone. The disparity in regional development within the Yangtze River Economic Belt is striking, manifesting not only in the weak integration and correlation of economic growth but also in the inconsistency of regional ecological construction. This has led to the coexistence of economically developed regions and ecologically compromised areas across the Yangtze River Economic Belt. In the context of China's strategic

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2302_30673089

transformation towards an ecological civilization, the carbon emissions associated with the diverse economic development models across the Yangtze River Economic Belt are evident. In the context of the national strategy for ecological civilization, there is a clear spatial heterogeneity in the carbon emission effect associated with different regional economic development models in the Yangtze River Economic Belt. Furthermore, the advantages of spatial ecological resources have yet to be fully utilized, and the ecological economy remains underdeveloped. Accordingly, this study focuses on the Yangtze River Economic Belt, a vast region spanning from east to west and exhibiting considerable disparities in development, to investigate the spatial variations in carbon emission effects across different regions and their patterns. This can elucidate the distinct impacts of industrial structure, economic advancement, and environmental policies on different regions, offering valuable insights for the formulation of targeted emission reduction strategies in the Yangtze River Economic Belt.

In light of the aforementioned considerations, the study employs a series of analytical techniques, including the calculation of carbon emissions from construction land, the utilization of the spatial autocorrelation model, the Terrell index, the standard deviation ellipse, and the center of gravity migration model, with the objective of elucidating the spatial disparities in carbon emissions between the upper, middle, and lower reaches of the Yangtze River Economic Belt, as well as within these regions. The objective is to investigate the factors that differentiate the effect of carbon emissions from construction land through the geographically-weighted regression model, which serves to establish a foundation for further exploration of the spatial spillover effect of carbon emissions between the upper, middle and lower reaches of the Yangtze River Economic Belt and the construction of a spatial association network. This will provide a foundation for further exploration of the spatial spillover effect of carbon emissions between the upstream, midstream and downstream regions, as well as the construction of a spatial correlation network. Additionally, it will offer a reference point for optimizing the spatial development pattern of the Yangtze River Economic Belt and achieving high-quality development.

Materials and methods

Sample and data source

China is currently in the development phase of the 20th National Congress. Since 2010, the Chinese government has been actively exploring the implementation of a dual-target control mechanism for the total amount of carbon emissions and the total amount of carbon emissions. This has involved the dual control of carbon emission intensity and the total amount of carbon emissions. In light of the aforementioned, this paper has selected the period spanning the 17th National Congress to the 19th National Congress as the research period, with a particular focus on the years 2009 to 2021. The construction land area data, socio-economic data and energy data used in the study come from the China Statistical Yearbook, China Urban Statistical Yearbook and China Energy Statistical Yearbook for 2010-2022. The study area is the Yangtze River Economic Belt. According to “the Outline of the Plan for the Development of the Yangtze River Economic Belt,” the upstream zone includes Chongqing, Sichuan, Yunnan, and Guizhou, the midstream zone includes Jiangxi, Hunan, and Hubei, and the downstream zone includes Shanghai, Jiangsu, Zhejiang, and Anhui.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
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Research methods

Estimation of carbon emissions

Carbon emissions from cropland, forest land, grassland, watershed and unutilized land are direct carbon emissions; carbon emissions from construction land are indirect carbon emissions. Indirect carbon emissions from construction land, refer to the IPCC energy carbon emission coefficient method, the formula is as follows:

$$C_e = \sum_{i=1}^{N} B_i \times D_i \times E_i \quad \text{(Eq.1)}$$

where: C_e is the carbon emission from construction land, t; B_i is the consumption of a fossil energy source, t; D_i is the conversion factor of standard coal (kg/kg); E_i is the carbon emission coefficient of fossil energy source (t/t, in C), and the conversion factor of standard coal and carbon emission coefficient refer to the China Energy Statistics Yearbook (*Table 1*).

Table 1. *Standard coal conversion factors and carbon emission factors for different energy type*

Energy type	Standard coal conversion factor	Carbon emission factor
Raw coal	0.7143	0.7559
Coke	0.9714	0.8550
Washed coal	0.9000	0.7559
Other washed coal	0.2857	0.7559
Gasoline	1.4714	0.5538
Kerosene	1.4714	0.5714
Diesel	1.4571	0.5921
Fuel oil	1.4286	0.6185

α-Convergence analysis

The α-convergence is used to express that carbon emissions from construction land in different regions deviate from the average value over time, i.e., the degree of dispersion decreases with the passage of time. The existing α-convergence is mostly characterized by the coefficient of variation, with the following formula:

$$CV = \frac{\sqrt{\frac{\sum_{i=1}^{n}\left(Y_i - \bar{Y}\right)^2}{n}}}{\frac{\sum_{i=1}^{n} Y_i}{n}} \quad \text{(Eq.2)}$$

where: Y_i is the carbon emission from construction land in year i; $\bar{Y}$ is the average value of carbon emission from construction land; n is the length of the study period.

Tyrell's index

The Theil index was first proposed by Theil when he employed the concept of entropy in information theory to quantify the disparities in regional income levels. The

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
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Theil index is capable of reflecting both inter-group and intra-group differences, thereby enabling a comprehensive reflection of the discrepancies between regions. It is employed extensively in a range of socio-economic contexts, including the assessment of economic development, eco-efficiency and scientific and technological innovation capacity. The calculation process is straightforward, the results are clear and concise, and it is an effective means of portraying inhomogeneity. It is evident that there are significant spatial variations in a number of key socio-economic indicators, including economic development, population density, industrial structure and energy consumption, across the upper, middle and lower reaches of the Yangtze River Economic Belt. Furthermore, there are notable differences in carbon emissions from construction land within the region itself. The Theil index is an effective tool for accurately capturing these spatial heterogeneities and their evolution. Theil index ranges from 0 to 1, the value is smaller, and the regional difference is smaller, the formula is:

$$T = T_{BR} + T_{WR} \tag{Eq.3}$$

$$T_{BR} = \sum_{k=1}^{n} \left(\frac{C_k^t}{C_{total}^t} \right) \ln \left(\frac{C_k^t / C_{total}^t}{R_k^t / R_{total}^t} \right) \quad \text{Eq.4)}$$

$$T_{WR} = \sum_{k=1}^{n} \left(\frac{C_k^t}{C_{total}^t} \right) \sum_{i=1}^{v} \left(\frac{C_{ki}^t}{C_k^t} \right) \ln \left(\frac{C_{ki}^t / C_k^t}{R_{ki}^t / R_k^t} \right) \tag{Eq.5}$$

where: T, T_{BR}, T_{WR} are the overall, inter-regional and intra-regional differences in carbon emissions from construction land; n is the number of regions; v is the number of provinces; C_k^t is the carbon emissions from construction land in region k in year t; C_{total}^t is the carbon emissions from construction land in the Yangtze River Economic Zone in year t; R_k^t is the area of construction land in region k in year t; R_{total}^t is the area of construction land in the Yangtze River Economic Zone in year t; C_{ki}^t is the carbon emissions from construction land in province i in region k in year t; R_{ki}^t for the area of construction land in province i in region k in year t.

Standard deviation ellipse (math.)

The standard deviation ellipse method is a well-established approach for analyzing the directional characteristics of spatial distribution, which can elucidate the morphological characteristics of spatial distribution of elements. The long half-axis of the ellipse indicates the direction of the spatial distribution of elements, while the short half-axis indicates the range of the distribution of elements. In cases where the long and short axes are in close proximity, the directionality of the distribution is less apparent (Wu et al., 2024).

Spatial auto-correlation analysis

Exploratory spatial data analysis is a collection of techniques used to analyze spatial data, the core of which lies in spatial auto-correlation to measure and test the spatial correlation pattern (convergence or heterogeneity) of the research object, mainly including global spatial auto-correlation and local spatial auto-correlation.

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Global spatial auto-correlation

Global spatial auto-correlation is mainly used to analyze the degree of spatial aggregation of the research object in the whole region, and the most commonly used is Moran's *I* index, whose calculation formula is:

$$\text{Moran's } I = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n}W_{ij}(X_i - \bar{X})\quad(X_j - \bar{X})}{\sum_{i=1}^{n}(X_j - \bar{X})\sum_{i=1}^{n}\sum_{j=1}^{n}W_{ij}} \tag{Eq.6}$$

where: n is the number of provincial regional units in the study area; X_i and X_j are the carbon emissions from construction land in regions i and j, respectively; is the mean value; and W_{ij} is the spatial weight matrix. The value range of Moran's I index is [-1,1], when Moran's $I < 0$, it indicates that there exists a When Moran's $I < 0$, it indicates the existence of negative spatial correlation, i.e. spatial heterogeneity; when Moran's $I > 0$, it indicates the existence of positive spatial correlation, i.e. spatial convergence; when Moran's $I = 0$, it indicates that the spatial distribution of carbon emissions from the construction land is independent of each other.

Local spatial auto-correlation

Local spatial auto-correlation is mainly used to analyze the degree of spatial aggregation of the research object in the local area, which is usually measured by Local Moran's *I* index, and its calculation formula is:

$$I_i = Z_i \sum_{j=1}^{n} W_{ij} Z_j \tag{Eq.7}$$

where: I_i is Local Moran's index, and Z_i and Z_j are the standardized values of the variance of carbon emissions from construction land in regions i and j, respectively.

Geography-weighted regression analysis

Geographically weighted regression (GWR) is a statistical method for quantifying spatial heterogeneity. It is suitable for dealing with data exhibiting spatially varying relationships and is designed to address the issue of heterogeneity in spatial data. The introduction of a spatial weighting matrix enables the parameters of the model to vary at each geographic location, thereby facilitating a more nuanced adaptation to local variations in spatial data. From a geospatial perspective, economic development, particularly at the regional level, is highly susceptible to spatial heterogeneity. The carbon emission effect of land use in the various regions of the Yangtze River Economic Belt is characterized by significant spatial heterogeneity, which can be attributed to the disparate industrial structures and energy consumption patterns observed across these regions. Consequently, the geographically weighted regression model allows for the exploration of the changing law of the factors influencing the carbon emission effect in the upper, middle and lower reaches of the Yangtze River Economic Belt in a highly intuitive and clear manner. This, in turn, enables the formulation of more targeted implementation measures that are in line with the actual

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
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development of the different regions in the upper, middle and lower reaches of the Yangtze River Economic Belt. Its calculation formula is:

$$y(u)=\beta_0(u)+\sum_{k=1}^{p}\beta_k(u)\times x_k(u)+\varepsilon(u) \quad \text{(Eq.8)}$$

where: $y(u)$ is the carbon emissions from construction land at a location u; $x_k(u)$ is the value of the k^{th} covariate at a location u; $\beta_k(u)$ is the regression coefficient of the k^{th} covariate; $\beta_0(u)$ is the intercept term; $\varepsilon(u)$ is the random error term at a location u.

Results

Characteristics of time-series changes in carbon emissions from construction sites

From the perspective of total carbon emissions, the total carbon emissions of the Yangtze River Economic Zone demonstrate an upward trajectory from 2009 to 2021, exhibiting a growth rate of 14.16%. The total carbon emissions of the upstream, midstream and downstream regions all demonstrate an increase, with growth rates of 0.20%, 17.17% and 22.66% respectively. Notably, the rise in the midstream and downstream regions is considerably higher than that observed in the upstream. The contribution of the downstream regions to the total carbon emissions of the Yangtze River Economic Belt is markedly higher than that of the midstream and upstream regions. With regard to carbon emission intensity, the overall trend in the Yangtze River Economic Belt demonstrates a downward trajectory, with a reduction of 16.31%. The carbon emission intensity of the upstream, midstream and downstream regions all exhibited a decline, with reductions of 33.38%, 8.56% and 5.35%, respectively. The combined analysis of total carbon emissions and carbon emission intensity reveals that the area of urban construction land in the upstream, midstream and downstream regions has increased. However, the recent increase in urban construction land is most pronounced in the upstream region, followed by the midstream region and then the downstream region. In terms of carbon emission per 10,000 people, the Yangtze River Economic Belt exhibits a pattern of downstream > middle-stream > upstream. Both the carbon emission intensity and the carbon emission per ten thousand people show a decreasing trend from east to west within the regional range, indicating that the spatial heterogeneity of construction land expansion and total population change is weaker than the spatial heterogeneity of carbon emissions. At the same time, apart from the potential additional demand for construction land expansion due to the construction of manufacturing bases and energy bases in the central region in the later period, the temporal variation in regional differences in carbon emission intensity is not obvious. The data indicate a downward trend in carbon emissions per 10,000 people in the Yangtze River Economic Belt, with a decrease of 71.27%. Furthermore, the upstream, midstream and downstream regions all exhibited a reduction in carbon emissions per 10,000 people, with decreases of 79.59%, 74.36% and 53.17%, respectively (*Fig. 1*).

Convergence analysis of carbon emissions

The α-convergence analysis of carbon emissions from construction land in the Yangtze River Economic Belt from 2009 to 2021 (*Fig. 2*) reveals that the coefficients of variation of carbon emissions from construction land in the Yangtze River Economic

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Belt, the upstream region of the Yangtze River Economic Belt, the midstream region and the downstream region are all characterized by small fluctuations in the change of carbon emissions. The coefficient of variation of carbon emissions from construction land in the Yangtze River Economic Belt demonstrates a notable decline from 0.33 in 2009 to 0.17 in 2021. A similar trend is observed in the upstream region, where the coefficient of variation decreases from 0.27 in 2009 to 0.17 in 2021. The midstream region and the downstream region also exhibit a reduction in the coefficient of variation, from 0.29 and 0.31 in 2009, respectively, to 0.18 in both regions in 2021. This suggests that the disparity in carbon emissions from construction land has diminished, exhibiting more pronounced α-convergence attributes.

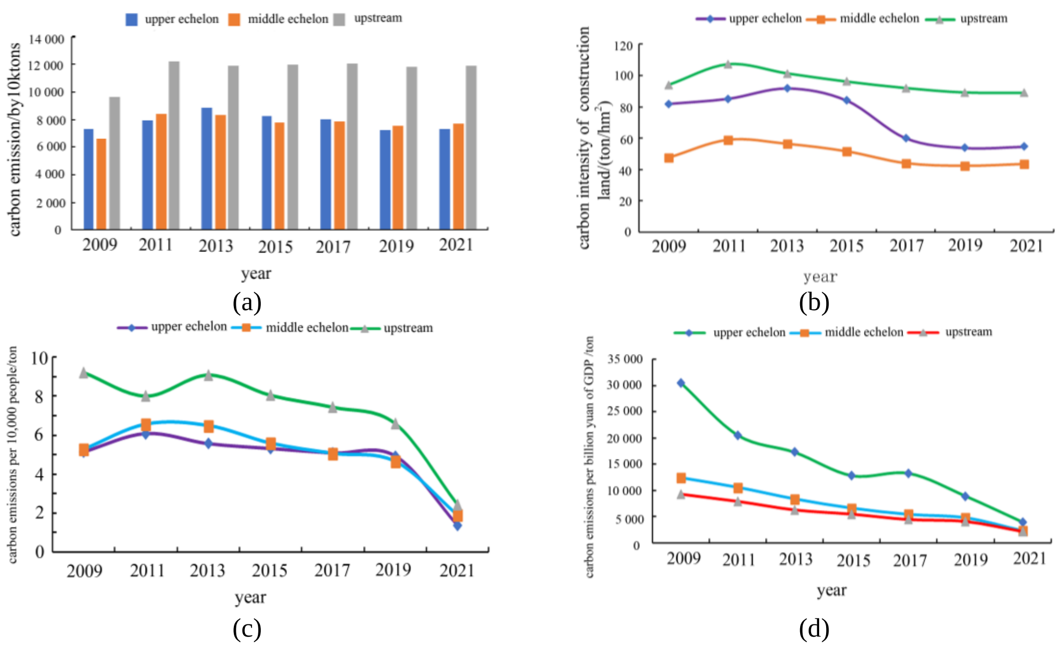

Figure 1. *Time-series characteristics of carbon emissions from construction land in the Yangtze River Economic Belt. (a) Chronological change in carbon emissions. (b) Time-series changes in carbon intensity. (c) Chronological change in carbon emissions per 10,000 population. (d) Change in time series of carbon emissions per billion yuan of GDP*

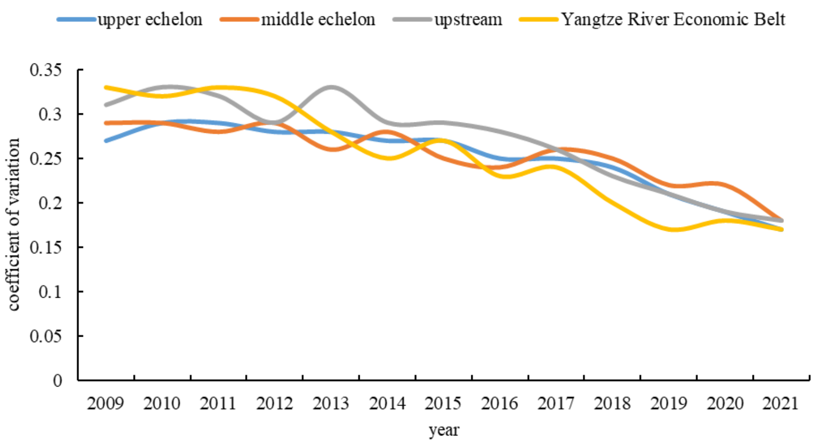

Figure 2. *Coefficient of variation of carbon emissions from construction land in the Yangtze River Economic Zone*

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Analysis of spatial effect of carbon emissions from construction land

Analysis of spatial changes in carbon emissions

Spatial distribution pattern of total carbon emissions. From 2009 to 2021, the total carbon emissions of the Yangtze River Economic Belt exhibited a discernible distribution trend, displaying a gradual decrease from east to west. This resulted in a spatial distribution pattern that followed the sequence downstream > midstream > upstream (*Fig. 3*). Two potential explanations for this phenomenon can be posited. Firstly, the downstream region of the Yangtze River Economic Belt, comprising Shanghai, Jiangsu and Zhejiang, constitutes the traditional Yangtze River Delta, exhibiting a distinct polarization in economic development. Historically, the Yangtze River Delta region has exhibited an unusually pronounced agglomeration effect on factors, with construction land carrying a highly saturated or even oversaturated scale of population and industry. This has resulted in a cumulative carbon emission effect that is significantly stronger than that observed in the middle reaches and the upstream. The spatial disparity between carbon emissions in the downstream region and those in the midstream and upstream regions is becoming increasingly pronounced. Secondly, the upstream zone comprises Sichuan, Chongqing, Guizhou and Yunnan. This region can be considered to belong to China’s first-step terrain unit. Its innate geographic location and topographic and geomorphological features have constrained the development of construction land in the region to a certain extent. This is evidently lagging behind that of the middle and downstream zones. Furthermore, the majority of these regions are characterized by a net population outflow, coupled with relatively low population and industrial density. This results in a comparatively lower total amount of carbon emissions than that of the middle and downstream zones. Additionally, the majority of these regions are characterized by a net population outflow, exhibiting relatively low population and industrial density. Consequently, the total carbon emissions generated in these areas are comparatively lower than those observed in the midstream and downstream regions.

Spatial distribution pattern of carbon emission intensity. The spatial distribution pattern of carbon emissions in the Yangtze River Economic Belt from 2009 to 2021 also exhibits an evident trend of decline from east to west. This is illustrated by the decreasing intensity of carbon emissions from the downstream, middle-stream, and upstream regions (*Fig. 4*). The underlying cause may be associated with the intensity and efficiency of land utilization. The lower reaches of the Yangtze River Economic Belt are characterized by a greater concentration of megacities and mega-cities, with a development pattern comprising city clusters superimposed on industrial zones. This is accompanied by a high population density and a significant presence of industrial activity. Concurrently, the rapid urbanization and industrialization have resulted in a significant expansion of construction land, accompanied by a dearth of new sources of construction land that can be developed and converted. Consequently, in the event of the failure of the path of the expansion of urban construction land outside the city, there has been a shift towards utilizing the potential within the construction land, namely the intensity of construction land development and utilization and the efficiency of construction land development and utilization. Consequently, the downstream region exhibits a markedly elevated carbon emission intensity of construction land in comparison to the midstream and upstream regions. This signifies a considerable surge in both the intensity and efficiency of the development and utilization of construction land.

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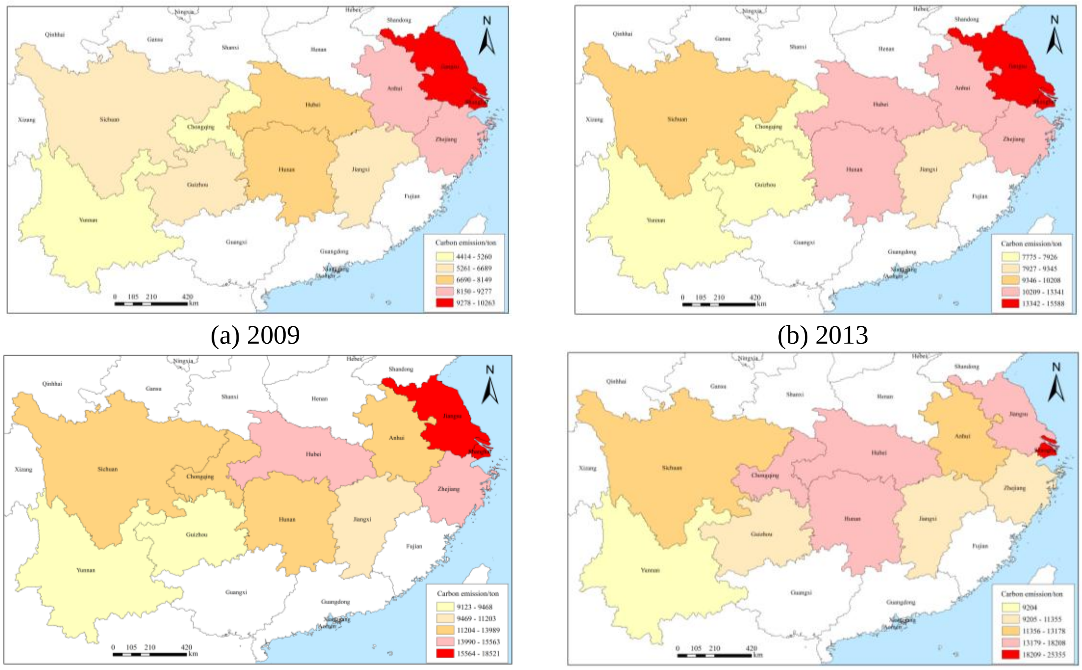
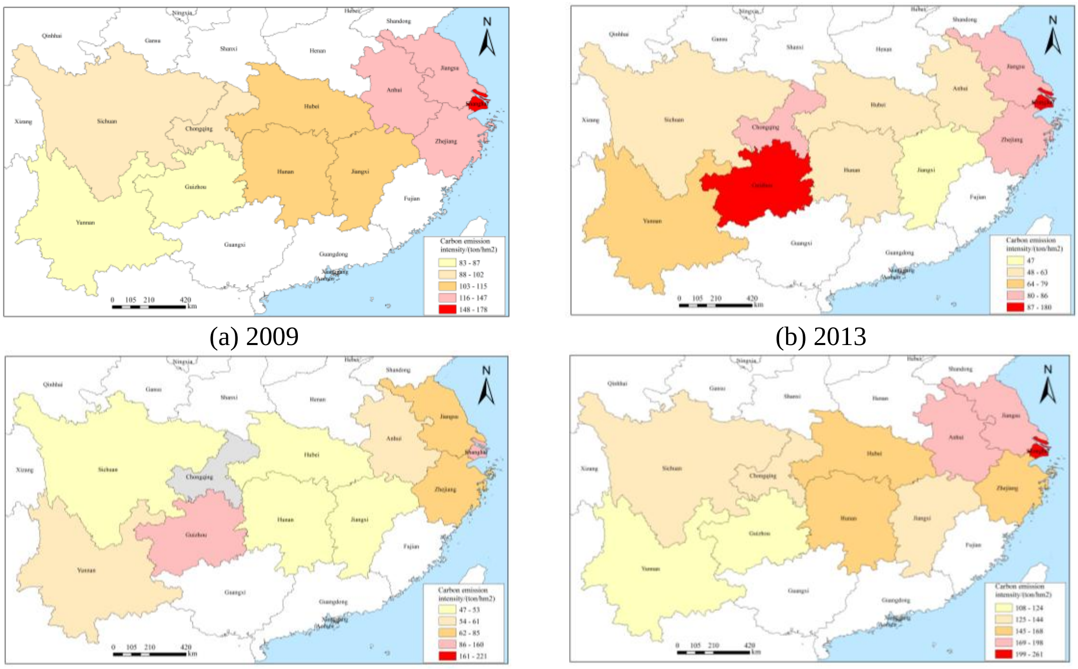


(a) 2009 (b) 2013

(c) 2017 (d) 2021

Figure 3. *Characteristics of spatial distribution of carbon emissions from construction land in the Yangtze River Economic Belt from 2009 to 2021*



(a) 2009 (b) 2013

(c) 2017 (d) 2021

Figure 4. *Spatial distribution characteristics of carbon emission intensity of construction land in the Yangtze River Economic Belt from 2009 to 2021*

In comparison to the downstream region, the upstream and midstream regions of the Yangtze River Economic Belt exhibit a lower carbon emission intensity, which is

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associated with their accelerated expansion of construction land. The middle and upper reaches of the Yangtze River are distinguished by a gradual process of urbanization and industrialization, a substantial scope for economic growth, and a decoupling of construction land expansion and economic development. Consequently, as a crucial foundation for economic advancement, the middle and upper reaches of the Yangtze River possess a relatively abundant supply of construction land for development, utilization, and conversion. The expansion of construction land has resulted in a relatively low carbon emission intensity of construction land in the context of urban development.

Analysis of differences in carbon emission intensity

Figure 5 illustrates the Tyrell’s index of carbon emission intensity in the Yangtze River Economic Belt. The overall difference in carbon emission intensity of construction land in the Yangtze River Economic Belt from 2009 to 2021 demonstrates a fluctuating and slowly decreasing trend, which aligns with the coordinated and integrated development strategy of the Yangtze River Economic Belt. Additionally, inter-region differences are increasing year by year, while intra-region differences are decreasing year by year. This is concurrent with the phase of China’s policy development. In 2009, China was in the initial phase of development, during which the country exhibited accelerated economic growth driven by the expansion of construction land. The downstream regions of the Yangtze River Economic Belt, including the traditional Yangtze River Delta (comprising Jiangsu, Zhejiang, and Shanghai), also demonstrated a parallel development pattern, characterized by a rapid increase in land urbanization. The quantitative effectiveness of economic development was also evident in the development path of the middle and upper reaches of the Yangtze River Economic Belt in 2009. The same unilateral expansion of construction land led to the path of urban development, resulting in relatively minor inter-regional differences at the outset of the early stage of development in 2009. However, by the second decade of the 21st century, these inter-regional differences became more pronounced. During the second decade, there was a notable increase in inter-regional differences, which may be attributed to the fact that the zoning of the Yangtze River Economic Belt has become increasingly clear, as has the development positioning of the various regions. The upstream region has a particular inclination towards ecological industrialization, which relies on the unique geographic location, derived from the advantages of spatial ecological resources, allows for a win-win situation to be achieved between the economy and ecology through the utilization of these resources. The mid-stream region has a greater number of manufacturing bases in China, while the downstream region is more saturated with population and industries. The downstream area is characterized by a high population density and a concentration of industrial activity. In contrast, the middle and lower reaches are more inclined towards industrial ecologization, which involves guiding existing scale industries to adjust and improve in an ecological direction. However, this process presents certain challenges, leading to a widening gap between the upstream and downstream regions. At the intra-regional level, the downstream region, comprising Jiangsu, Zhejiang and Shanghai, exhibits a higher degree of integration in terms of population density and industrial development. The development positioning of the overall manufacturing base in the midstream region contributes to the greater perfection of the manufacturing industry development system. The upstream region is situated at the same level as the first rung of China’s industrial ladder and exhibits similar development location conditions. Consequently, the intra-

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regional differences are demonstrating a decreasing trend on the whole. With regard to the contribution rate of differences, the contribution rate of intra-regional differences is markedly higher than that of inter-regional differences. The former demonstrates a declining trend, while the latter exhibits an increasing trend.

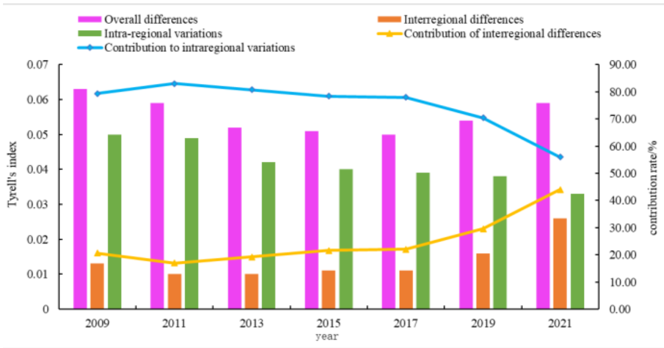

Figure 5. *Tyrell's index and contribution rate of carbon emission intensity of construction land in the Yangtze River Economic Zone from 2009 to 2021*

Evolution of spatial patterns of carbon emissions

The center of gravity of carbon emissions from 2009 to 2021 is located within Hubei province, with a gradual westward migration observed over 12 years. During this time, the center of gravity exhibited a longitudinal shift of 0.55° and a latitudinal shift of 0.07°. The long semiaxis of the standard deviation ellipse demonstrates an increase from 942.74 km in 2009 to 946.40 km in 2017, followed by a subsequent decrease to 939.84 km in 2021. This suggests that the spatial evolution of direction of carbon emissions from construction land is relatively less stable in the northeast-southwest direction; the short semiaxis of the standard deviation ellipse increases from 259.47 km in 2009 to 261.46 km in 2017, and then decreases to 251.10 km in 2021. This indicates that the spatial distribution of carbon emissions from construction land is characterized by a concentration and tightening in the north-west-south-east direction. The azimuth angle demonstrates a gradual expansion, indicating a constant shift in the carbon emissions from construction land in the Yangtze River Economic Zone in a clockwise direction (*Fig. 6*).

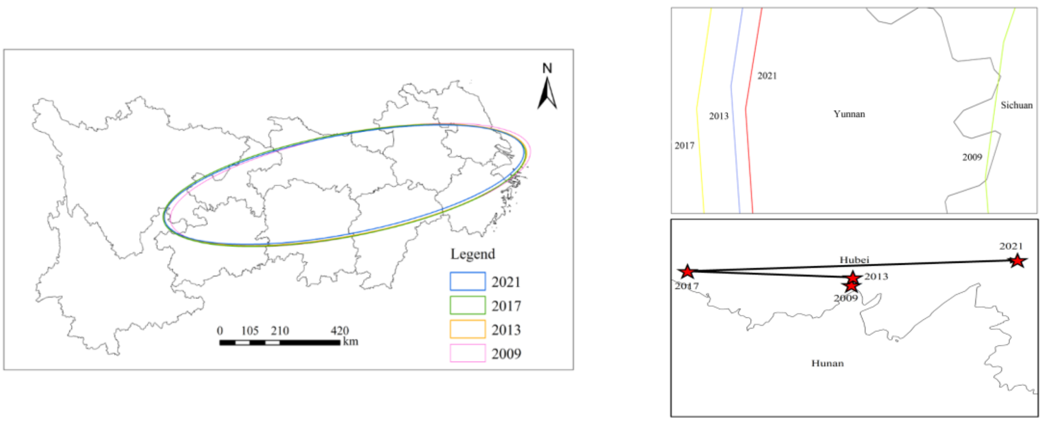

Figure 6. *Standard deviation ellipse and center of gravity trajectory of carbon emissions from construction land in the Yangtze River economic belt*

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Spatial auto-correlation analysis of carbon emissions

Global auto-correlation analysis

Global Moran's *I* of carbon emissions from construction land in the Yangtze River Economic Belt was calculated and summarized from 2009 to 2021 based on the spatial auto-correlation tool in ArcGIS. The spatial auto-correlation and degree of agglomeration of carbon emissions were then explored from the overall spatial perspective (*Table 2*).

Table 2. *Global Moran's I of the Yangtze River Economic Belt from 2009 to 2021*

Year	Moran's *I*	*Z* value	*P* value
2009	0.533	3.131	0.002**[a]
2010	0.469	2.844	0.004**
2011	0.407	2.533	0.011**
2012	0.477	2.851	0.004**
2013	0.478	2.869	0.004**
2014	0.466	2.830	0.005**
2015	0.479	2.941	0.002**
2016	0.393	2.529	0.011**
2017	0.406	2.621	0.009**
2018	0.352	2.146	0.065*[b]
2019	0.281	2.008	0.004**
2020	0.328	2.786	0.004**
2021	0.321	2.667	0.005**

**0.05 significance level; *0.1 significance level

As illustrated in *Table 2,* the global Moran's I for the period between 2009 and 2021 is greater than 0 for all locations, and is significant at the 10% level or above. This indicates that the spatial distribution of carbon emissions from construction land in the Yangtze River Economic Belt exhibits a significant positive spatial agglomeration. The global Moran's *I* from 2009 to 2021 is situated predominantly within the range of 0.3-0.5, indicating that the spatial agglomeration of carbon emissions from construction land in the Yangtze River Economic Zone is relatively stable, exhibiting only minor inter-annual fluctuations.

Local auto-correlation analysis

To further examine the spatial clustering of carbon emissions from construction sites in the Yangtze River Economic Zone, this study conducted a local auto-correlation analysis of carbon emissions from construction sites in the Yangtze River Economic Zone in 2009 and 2021 (*Fig. 7*). *Figure 7* illustrates that in 2009, Shanghai and Jiangsu exhibited a HH-type pattern, indicating a high concentration of carbon emissions from construction sites, while Sichuan and Guizhou displayed an LL-type pattern, indicating a low concentration of such emissions. In 2021, Shanghai, Jiangsu and Zhejiang exhibited a HH-type pattern, while Sichuan, Guizhou and Hunan exhibited an LL-type pattern. Both are relatively stable.

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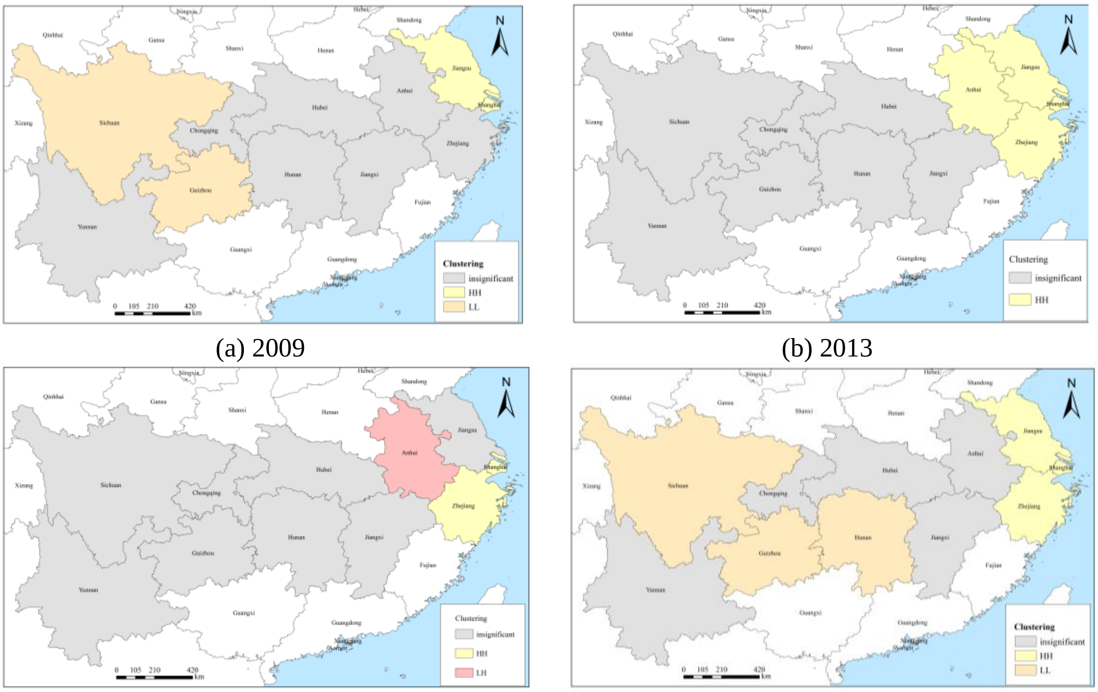


(a) 2009 (b) 2013

(c) 2017 (d) 2021

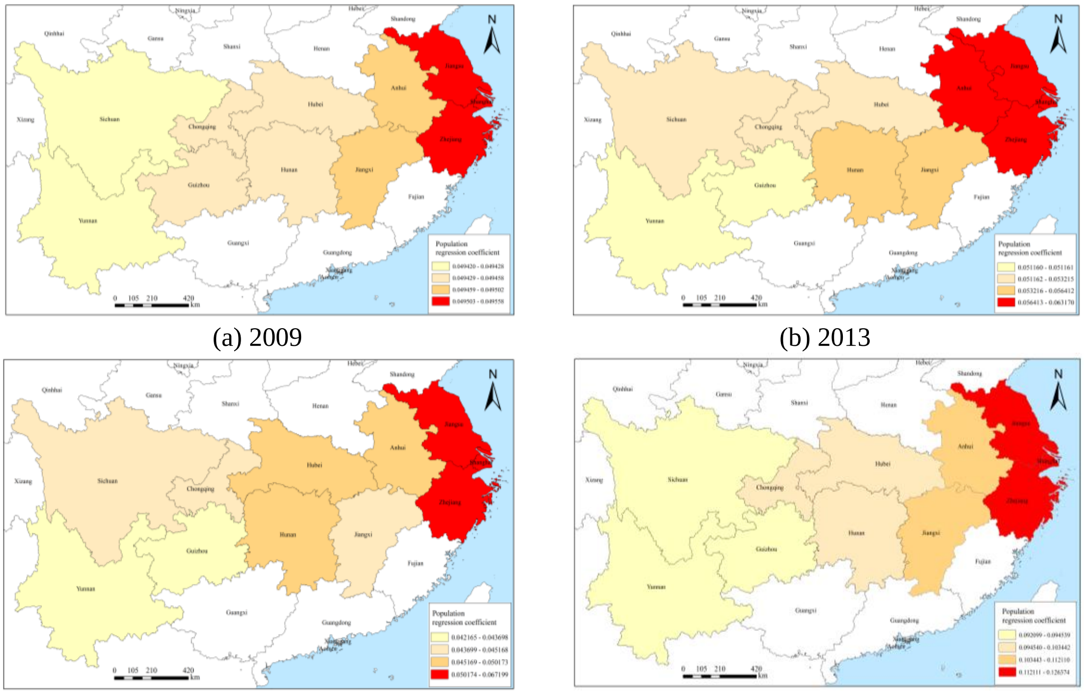
***Figure 7.** LISA clustering of carbon emissions from construction land in the Yangtze River Economic Zone from 2009 to 2021*

Analysis of carbon emission driving factors of construction land use

The study examines the factors that contribute to carbon emissions from construction land, considering four key areas: population, industry, energy and land. In consideration of the necessity for multi-collinearity of variables, the final selection of factors for analysis comprises the resident population, the proportion of output value of secondary and tertiary industries, total energy consumption, and the area of construction land.

Influence of resident population on carbon emissions from construction land use

As illustrated in *Figure 8*, a positive correlation is evident between the resident population and construction land carbon emissions, with the regression coefficient for the impact of the resident population in 2009 distributed at 0.049420-0.049558. The areas with the greatest impact were concentrated in the Jiangsu, Zhejiang and Shanghai regions, while the upstream areas, particularly those in Sichuan and Yunnan Provinces, exhibited a relatively lower degree of impact. In 2021, the influence of the resident population is generally increased, with the influence regression coefficient distributed at 0.092099-0.126374. Meanwhile, in the area surrounding Jiangsu, Zhejiang and Shanghai, the influence of the resident population in the middle and upper reaches of the region is significantly increased. This may be attributed to the fact that the upstream region capitalizes on the developmental opportunity presented by the strategic transition period of China’s ecological civilization. It fully exploits the advantages offered by the local geographic resources, thereby driving continuous improvement in the relevant industrial chain. This, in turn, increases the demand and attraction for the region, which, on the one hand, has prompted a reversal of the previous long-term exodus of people, and on the other hand, the unique combination of natural resources has given rise to new industries, such as recreation and healthcare. This has created opportunities for entry into the upstream region, including Yunnan, Guizhou, and Chongqing. The provinces of Yunnan, Guizhou and Chongqing, along with other regions within the region, are increasingly appreciating the region's natural resources. The number of people living there is also on the rise. When viewed in a comprehensive manner, the new era's national policy, coupled with the upstream region's provinces and cities, has led to a notable surge in the resident population. This, in turn, has resulted in a significant rise in the production and living activities of people, which has led to an increase in carbon emissions. The degree of impact on carbon emissions has also increased.



(a) 2009 (b) 2013

(c) 2017 (d) 2021

Figure 8. *Distribution of the impact of resident population on carbon emissions from 2009 to 2021*

Influence of industrial structure on carbon emissions from construction land use

As illustrated in *Figure 9*, there is a positive correlation between industrial structure and carbon emissions from construction land. In 2009, the regression coefficient of the influence of industrial structure ranged from 0.482204 to 0.886956. The regions with greater influence were also concentrated in the area of Jiangsu, Zhejiang and Shanghai, while the influence of Sichuan, Chongqing and Yunnan-Guizhou was smaller. In 2021, the degree of influence of industrial structure was generally increased, with the regression coefficient distributed between 0.931433 and 1.230983. The degree of influence of industrial structure in upstream regions was significantly weaker than that in downstream regions. The rationale may be attributed to the fact that the construction land space is primarily occupied by secondary and tertiary industries, while the downstream region is situated in a flat and open terrain. This presents a distinct economic and geographical advantage, particularly for the development of secondary

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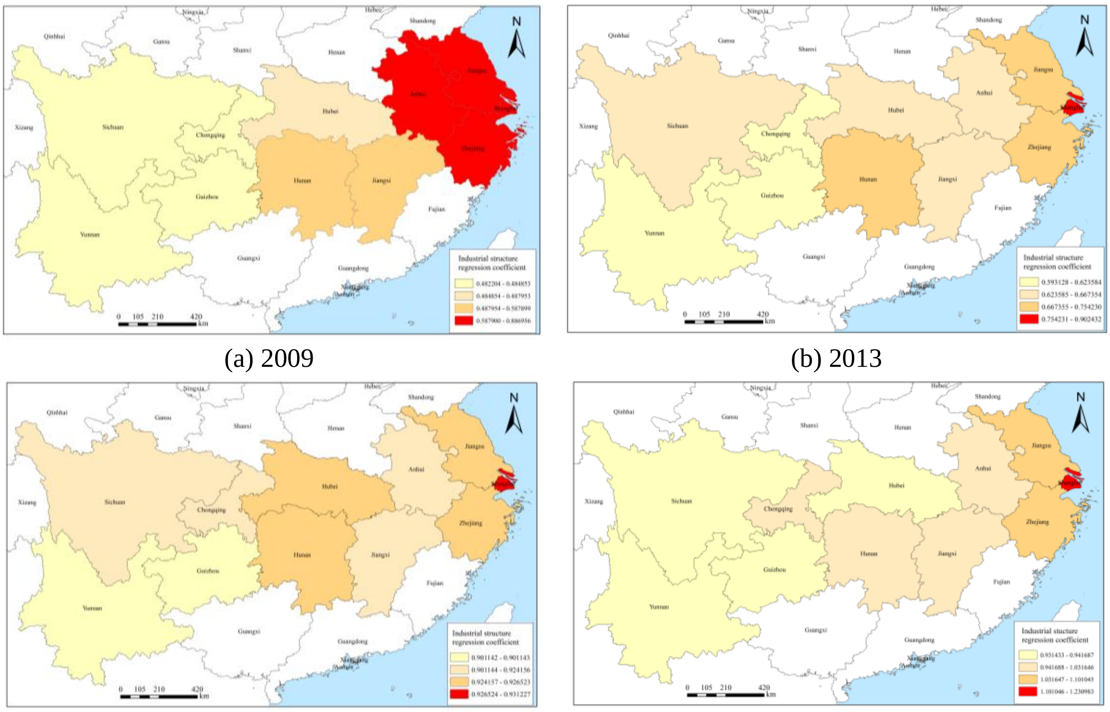
and tertiary industries, which enjoy a unique advantage in this region. The concentration of resources, including land, capital, human resources and technology, has led to a saturation or even supersaturation of industries in the construction land space. The industrial structure system is now more complete, and the carbon emission effect associated with the development of these industries is more evident. The industrial structures of the Sichuan-Chongqing and Yunnan-Guizhou regions have become increasingly influential, yet their industrial development is constrained by topographical and geomorphological features. Consequently, the limited carrying capacity of natural resources precludes the possibility of over-dense industrial distribution. Instead, industrial development in these regions is oriented towards ecology, resulting in a spatial variability in the degree of influence of industrial structure.



(a) 2009 (b) 2013

(c) 2017 (d) 2021

Figure 9. *Distribution of the impact of industrial structure on carbon emissions from 2009 to 2021*

Influence of energy consumption on carbon emissions

As illustrated in *Figure 10*, there is a positive correlation between energy consumption and carbon emissions from construction land. The regression coefficient of the impact of energy consumption in 2009 was distributed between 0.095885 and 0.535320. The regions with the greatest impact were concentrated in Shanghai and Zhejiang, while the degree of impact in Sichuan, Yunnan, and Guizhou was comparatively smaller. Furthermore, the highest value of the impact of energy consumption in 2021 was reduced, and the regression coefficient of the impact was distributed between 0.207118 and 0.496990. This indicates that the degree of influence of energy consumption in the upstream region is significantly weaker than in the downstream region. The impact of energy consumption in the downstream region is

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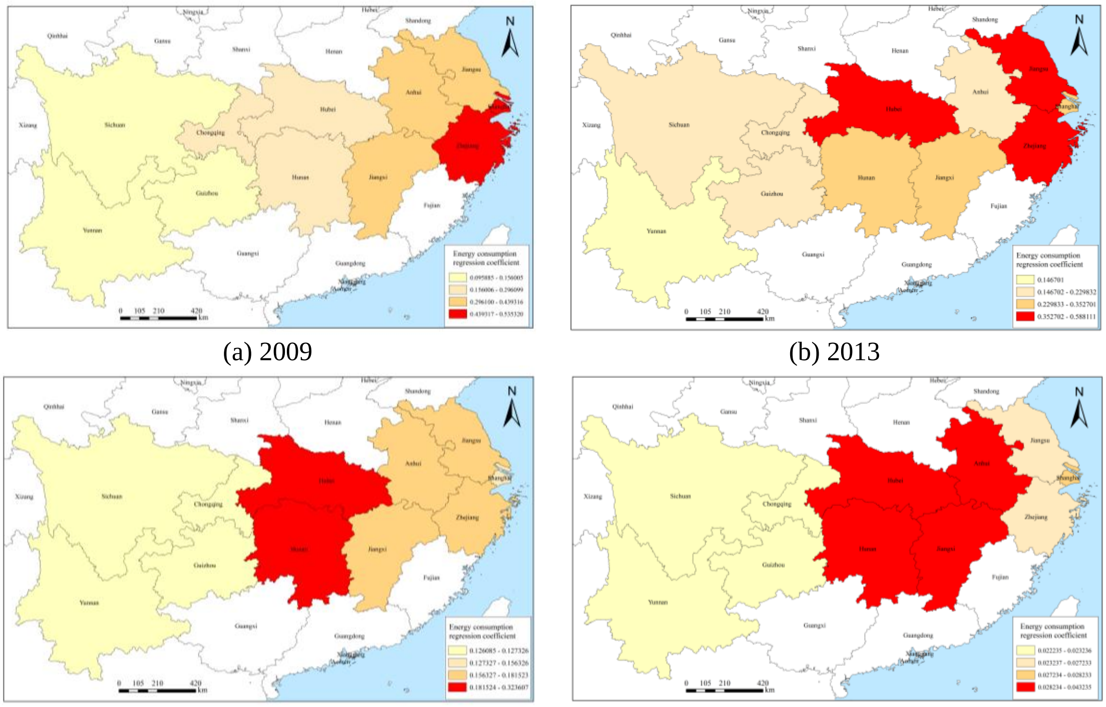
observed to diminish, while that of the midstream region is seen to increase. This may be attributed to the necessity of transforming the industrial development mode and reducing the degree of dependence on polluting energy in the previous development mode, as required by the national ecological civilization strategic transformation. This is reflected in the more obvious cases of Jiangsu and Zhejiang Provinces, where the development of ecological civilization is effective and the degree of influence of traditional energy consumption on carbon emissions has decreased significantly. The development orientation of the midstream region involves the construction of manufacturing bases. In the short term, it is challenging to eliminate the reliance on traditional energy sources and achieve the decoupling of the economy and energy consumption. Consequently, traditional energy consumption continues to exert a considerable influence on carbon emissions.



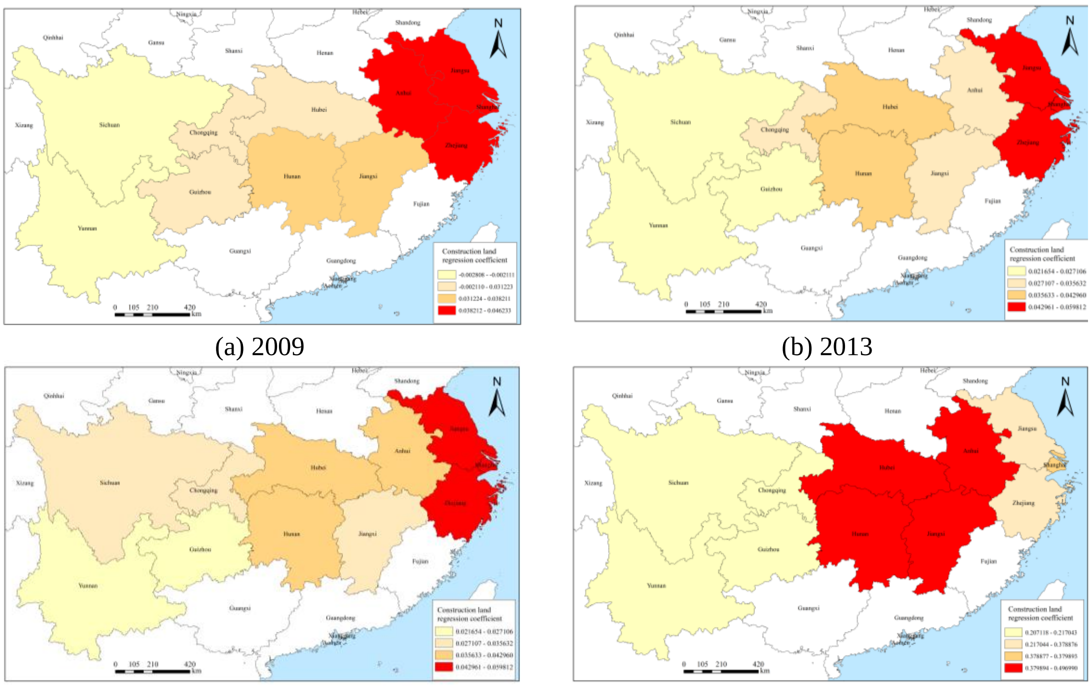
(a) 2009 (b) 2013

(c) 2017 (d) 2021

Figure 10. *Distribution of the impact of energy consumption on carbon emissions from 2009 to 2021*

Influence of construction land on carbon emissions

As illustrated in *Figure 11*, the correlation between construction land and carbon emissions was negative in the upstream regions and Hubei Province of midstream regions, and positive in the rest in 2009. The regression coefficients for the impact of construction land ranged from -0.002808 to 0.046233. The regions with the greatest impacts were mainly concentrated in the downstream region. In 2021, construction land and carbon emissions demonstrated a positive correlation, and the highest value of the degree of impact was reduced. Conversely, the degree of impact of construction land in the midstream region increased, while that of construction land in the downstream region also increased. In 2021, there was a positive correlation between construction land and carbon emissions, with the highest value of the influence degree reduced. The influence regression coefficient was distributed in the range of 0.021233-0.043235. The influence degree of construction land in the middle reaches of the region increased, while that in the downstream region decreased. The reason may be found in the fact that during the initial phase of development in 2009, the Yangtze River Economic Belt as a whole exhibited a rapid expansion of construction land and economic development, with the construction land in the upstream region also undergoing expansion. The region’s attractiveness to factors such as manpower, capital, and technology was relatively weak, resulting in a lack of notable population and industrial density growth in the upstream region. Additionally, the incidental increase in carbon emissions was relatively limited in scope. In 2021, as the concept of ecological civilization in the new era deepened, the industrial system in the downstream region became more mature and perfect. Consequently, the ecological adjustment of industry no longer required the expansion of construction land, which meant that the influence of construction land on carbon emissions decreased. The upstream region, having undergone a period of accumulation and development, has become an increasingly attractive location for human resources and other factors. Consequently, the population has begun to return, and the expansion of construction land and economic development have not achieved a complete separation of these two factors. To some extent, the expansion of construction land has not been completely decoupled from economic development, resulting in an increased impact on carbon emissions. In the middle reaches of the region, the most significant impact of construction land on carbon emissions is associated with the development of its manufacturing industry. The expansion of construction land, to a certain extent, can also stimulate the potential for economic development, with a more pronounced effect on carbon emissions.



(a) 2009 (b) 2013

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Figure 11. *Distribution of the impact of construction land on carbon emissions from 2009 to 2021*

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Discussion

In terms of the selection of research areas, studies conducted by Yang et al. (2024), Liu et al. (2024), Gao et al. (2024), Cai and Li (2024), and Xu and Li (2024) were conducted at the national, regional, provincial and municipal levels, respectively. In contrast, fewer studies were conducted on the Yangtze River Economic Belt at the regional level. Sunna et al. (2024) selected the three major urban agglomerations in the Yangtze River Economic Belt as an entry point to analyze the regional differences and spatial variability of carbon emissions from land use. However, taking the upper middle and lower reaches as an entry point is more aligned with China's current approach to regional development strategy in the Yangtze River Economic Belt. Yuan and Tang (2019) also examined the spatial variability of carbon emissions in the Yangtze River Economic Belt, yet they did not elucidate the underlying causes of this variability. This study examines the evolution of carbon emissions from construction land across the Yangtze River Economic Belt, aligning with the distinctive attributes of regional development within this economic zone. It also reflects the strategic transformation of China's ecological civilization, offering a valuable contribution to theoretical research in this field. The study analyses the characteristics of spatial differentiation of carbon emissions and the spatial variability of carbon emissions in the region and between regions. It addresses the limitations of existing studies through the use of a geographically weighted regression model. Furthermore, it bridges the gap between existing studies by employing geographically weighted regression models to investigate the spatial heterogeneity of carbon emission influencing factors in the Yangtze River Economic Belt. This is of paramount importance for the upper, middle, and lower reaches of the Yangtze River Economic Belt to devise targeted optimization measures and achieve regional integration and high-quality coordinated development in the context of the strategic transformation of the ecological civilization. In the future, on this basis, with the help of the gravity model, the spatial spillover effect of carbon emissions in the upper, middle and lower reaches of the Yangtze River Economic Belt and its spatial correlation network can be more comprehensively explored. This will enable the formulation of targeted optimization measures from the perspective of correlation and heterogeneity, thus facilitating the integrated and high-quality development of the Yangtze River Economic Belt.

Conclusion

(1) The total carbon emissions from construction land in the Yangtze River Economic Belt demonstrate an upward trajectory, with the total carbon emissions in the upstream, middle reaches and downstream increasing by 0.20%, 17.17% and 22.66% respectively. The intensity of carbon emissions exhibits a decreasing gradient from east to west, with the overall difference between regions gradually diminishing. Conversely, the inter-regional difference is on the rise, while the intra-regional difference is declining. (2) Both total carbon emissions and intensity demonstrate a downstream > midstream > upstream pattern, exhibiting a significant and stable positive spatial agglomeration. The highest values of carbon emission hotspots are concentrated in the downstream region, while the lowest values are located in the upstream region. The center of gravity of carbon emissions is located in Hubei Province and gradually shifts westward over time. During the 12-year period, the center of gravity moved 0.55° in the longitudinal direction and 0.07° in the latitudinal direction. However, the spatial

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
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evolution in the northeast-southwest direction is relatively unstable. (3) There is a positive correlation between the resident population, industrial structure, energy consumption and carbon emissions, with the most significant influence observed in the Jiangsu, Zhejiang and Shanghai regions. The correlation between upstream construction land and carbon emissions has undergone a notable shift, initially exhibiting a negative correlation and subsequently a positive one, with the impact of construction land in the middle reaches increasing and then declining in the lower reaches.

In the upstream areas, the objective is to transform the ecological value of the “green mountains” into an economic advantage, which will be realized as the “silver mountains.” The fundamental objective is to achieve eco-industrialization through a progressive transition from ecological resources to ecological assets and ultimately to ecological capital. Consequently, through the process of eco-industrialization, which is initiated from the specific regional characteristics of the area in question, the economic disadvantages associated with karst landforms are transformed into distinctive advantages for the advancement of an eco-economy. Additionally, tourism clusters comprising resources centered on karst landform landscapes are established, and elements of science education are integrated into eco-tourism. This integration encompasses the creation of distinctive landscapes, exemplified by peak clusters, stone forests, sinkholes and caves, among others. Furthermore, the combination of eco-relaxation tourism with science and culture through the utilization of digital technology is also facilitated. The combination of digital technology, ecological leisure tourism and the popularization of science facilitates the construction of a green ecological industry chain. The initial stage of the industry chain is based on contemporary digital technology, which is dedicated to showcasing regional spatial ecological resources in a comprehensive and innovative manner. The subsequent stage is enhanced by the distinctive geomorphic landscapes and traditional folk culture, which integrate the natural and humanistic landscapes into a unified entity, thereby stimulating the emergence of a new growth point in the economy. The final stage of the chain is concluded by the leisure and cultural tourism, recreation and healthcare modes, which collectively form a closed industry chain and foster the concept of “attracting people to come and staying with us.” This constitutes a virtuous cycle, whereby visitors are attracted to the area and then encouraged to remain there for an extended period of time.

The midstream region’s role in China’s national manufacturing base development strategy has resulted in a continued reliance on coal and other energy sources in the short term. However, the region can achieve carbon emission reduction on a larger scale through the “gas-for-coal” and enhanced coal cleaning techniques. Conversely, as industrial development progresses, advanced technology can be employed to facilitate deep processing, high-tech industries and new industries. These include energy-saving and environmentally-friendly sectors such as biomedicine, the digital economy and other ecologically-sensitive green industries. In a hierarchical and stage-by-stage manner, these will gradually supersede the backward industries with high energy consumption, high pollution and low production capacity. This will facilitate the iteration of industry.

In downstream areas, the objective is to transform the capital advantage of the “mountains of gold” into the ecological value of the “mountains of green water.” The fundamental objective is to facilitate the growth of green finance, industrial transformation and the development of forestry carbon sink industries, with the ultimate goal of achieving industrial ecology. The downstream areas have a high level of

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economic development, strong capital accumulation, and a concentration of high-tech and high-precision human resources, which allows them to effectively integrate industrial capital and financial capital, promote industrial transformation and upgrading by guiding the flow of resources, and stimulate enterprises to implement technological innovation and green transformation by providing tilted policy support, such as credits, guarantees, and compensations for eco-products. From the perspective of urban-rural integration, local ecological industrialization should be regarded as the principal objective of development. In this context, the development model of Yucun, Anji County, Zhejiang Province, offers a promising example of how to encourage citizens to relocate to the countryside, provided that appropriate financial incentives are in place. To achieve the effective circulation of capital, senior technicians, land, and other factors between urban and rural areas, and to fully leverage the advantages of the high rate of forest and grassland coverage, and to stimulate the development of sightseeing agriculture, leisure and tourism, ecological recuperation, and other industries. Furthermore, this approach allows for the full exploitation of the geographical location and land resources of the local area, while also addressing the issue of excess production capacity and capital. It also supports the concept of green ecological construction within the emerging development space, and enables the valorization of spatial ecological resources through financial capital, thus facilitating the development of a green economy.

Acknowledgements. This study was supported by Natural Science Foundation of Hebei Province (Contract No. D2015403033).

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