

Original Research

Spatiotemporal Evolution and Driving Forces of the Carbon Emissions of the Yangtze River Delta Urban Agglomeration

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Received: 5 September 2022

Accepted: 12 December 2022

Abstract

International hot topics such as carbon emission reduction and carbon neutrality and the growing regional ecological problems highlight the importance of low carbon development, and strengthening regional carbon emission research is increasingly important for exploring the path of global sustainable development in the new era. This study uses global and local spatial autocorrelation, geographic Detectors and Gini coefficients to carry out a dynamic comparative analysis of the spatial and temporal patterns of carbon emissions per capita of 41 cities in the Yangtze River Delta (YRD) urban agglomeration from 2006-2018 and to explore the driving forces. The results indicate that:

1) Over the study period, the per capita carbon emissions of the entire YRD urban agglomeration exhibited a “slow and subsequently sharp” continuous increase, while the corresponding Gini coefficient exhibited a “decreasing and subsequently increasing” trend.

2) Per capita carbon emissions at the city scale were spatially divergent from north to south, with the Yangtze River being the dividing line. Shanghai, Nanjing, Hangzhou and other municipalities or provincial capitals had much higher per capita carbon emissions than those of other cities, with the spatial “Matthew effect” being more obvious.

3) Per capita carbon emissions of the YRD urban agglomeration exhibited significant positive spatial correlations during the study period, with the high–high agglomeration cities gradually moving to the northwest and the low–low agglomeration cities remaining basically unchanged and but away from steady states slowly.

4) The gross industrial product, urbanization rate, and road length were the main drivers of increased per capita carbon emissions in this region; therefore, carbon reduction initiatives of local governments

should fully consider any urban differences and play exemplary leading roles in developed cities and provincial capitals.

Keywords: per capita carbon emissions; spatial and temporal evolution, geographic detectors, the Yangtze River Delta urban agglomeration

Introduction

Owing to the increasing severity of the greenhouse effect, prominent economies worldwide have gradually developed carbon reduction policies to mitigate climate change [1]. On September 22, 2020, at the General Debate of the 75th Session of the United Nations General Assembly, general secretary Xi announced that China would strive to peak its carbon dioxide emissions by 2030 and achieve carbon neutrality by 2060. Despite the efforts of Chinese governments at all levels to promote low-carbon development, reducing carbon emissions remains a pressing matter considering the need for concurrent sustained economic growth [2]. As the ‘fulcra’ of urban agglomerations, prefecture-level cities are the central cities of their respective economic zones and ‘transit points’ between first- and second-tier cities and the counties under their jurisdiction [3]. Research on carbon emissions at the prefecture-level city scale, which accurately outlines the spatial and temporal evolutions of carbon emissions and the factors influencing them, is an important reference for promoting regional green development and improving the accuracy and relevance of local government policies on energy conservation and emission reductions.

Considerable research has focused on the spatial and temporal evolutions and influencing factors of carbon emissions. In terms of the spatial and temporal evolutions of carbon emissions, Lin et al. used a two-stage Super-SBM-based model to analyze the spatial and temporal evolution characteristics of the carbon emission efficiency of industries and industrial sectors in the Beijing-Tianjin-Hebei region from 2000 to 2018 [4]. Wang and Du used a super-efficient SBM-DEA model and the Malmquist index to analyze the carbon emission efficiency of 14 cities (states) in Hunan Province from 2010 to 2016 [5]. Other studies on China’s provincial carbon emissions revealed their significant spatial differentiation and the presence of agglomeration effects, with the main carbon emissions from energy consumption and transportation being distributed in the eastern coastal region [6, 7]. Regarding the factors influencing carbon emissions, Deng, Liu, and Wang found that not only population size but also energy intensity and structure exert impacts on carbon emissions by using the log-averaged Deise index (LMDI) method [8]; Huang et al. revealed that the effect of industrial structure on carbon emissions has a catalytic effect by building an M-R model [9]. Wang et al. used panel quantile regression and found that population density and government expenditure have suppressive effects on per capita carbon emissions

in counties [10]. In addition, transportation, openness to the outside world, capital investment, population size, energy consumption, and agricultural development may also inhibit or promote carbon emissions [11-20].

In summary, the available wealth of research on regional carbon emissions constitutes a valuable reference for this study; however, most existing studies on carbon emission reductions are at the national or provincial scales, and few relevant studies focus on the prefecture-level city scale. In addition, many studies have used spatial econometric models, such as kernel density estimation, Markov chains, and spatial Durbin models, to explain the magnitude of the relationship between the spatial patterns of carbon emissions and the corresponding influencing factors. These studies have somewhat overlooked the different development stages in different provinces and regions, which is not conducive to proposing targeted localized carbon reduction strategies according to local conditions.

The YRD urban agglomeration plays an important role in China’s carbon emission reduction and carbon neutral strategy as it has high population mobility, developed economy and huge carbon reduction potential based on being one of the six largest urban agglomeration in the world. In the current context of global green development and low carbon development, the YRD urban agglomeration is a good case for studying the spatial and temporal patterns of carbon emissions, especially for regions with the contradiction between carbon reduction and economic development. The management and reduction experience here can be used as a reference for other mega-urbanized regions in the world. In the meantime, China is undergoing rapid urbanization and about 85% of CO₂ emissions are associated with energy consumption among cities [21]. Therefore, there is an urgent need to conduct regional carbon emission reduction studies at the city scale, as it is the basis to achieving China’s emission reduction goals. It helps us to undertake “common but differentiated reduction responsibilities”, so as to promote urban green transformation.

This study has two research objectives: The first objective is to explore the spatiotemporal evolution of carbon emissions of the YRD urban agglomeration at the city level, which further enriches the results regarding the heterogeneities of spatial and temporal patterns of carbon emissions at different scales and regions; the second objective is to reveal possible socio-economic factors using the geographical detector model, which also provides a theoretical basis for the next stage of promoting differentiated and distinctive carbon reduction strategies in the YRD urban agglomeration.

per capita in the YRD urban agglomeration. The former is mainly used to portray the overall distribution of per capita carbon emissions in cities to determine whether there is spatial agglomeration in the changes of per capita carbon emissions; the latter is to calculate and analyze the spatial correlation among cities themselves in the YRD urban agglomeration and their neighbors, aiming to reflect the spatial heterogeneity and instability in the local area. ArcGIS10.2 was used for calculating Moran's I index and exploring whether the spatial distribution of carbon emissions per capita of the YRD urban agglomeration has clustering characteristics. The spatial econometric analysis software GeoDa is used for producing a Anselin Local Moran's I index as well as a scatter plot of per capita carbon emissions of the YRD urban agglomeration, while classifying these emissions into four aggregation types: "high-high, low-high, low-low and high-low". The four types of clustering can reveal the local spatial clustering pattern and discrete characteristics of per capita carbon emissions in the YRD urban agglomeration. Global and Local spatial autocorrelation is calculated as follows:

$$Global\ Moran's\ I = \frac{[n/\sum_{i=1}^n(y_i-\bar{y})^2]\sum_{i=1}^n\sum_{j=1}^nw_{ij}(y_i-\bar{y})(y_j-\bar{y})}{\sum_{i=1}^n\sum_{j=1}^nw_{ij}} \tag{1}$$

$$Local\ Moran's\ I = \frac{(y_i-\bar{y})\sum_{j=1}^n(y_j-\bar{y})}{\sum_{i=1}^n(y_i-\bar{y})^2} \tag{2}$$

where w_{ij} denotes the spatial weight matrix; n is the number of study samples; y_i is per capita carbon emissions of a city i ; and \bar{y} is the average per capita carbon emissions in the sample cities [22].

Geographical Detectors

Geographic detectors can detect spatial differentiation of geographic phenomena and uncover their driving mechanisms [23]. The basic principle of geographic detectors is that if the independent variable has a strong influence on the dependent variable, then there is a certain similarity in its spatial distribution [24]. This study detects the influence of each driving forces on the spatial variation of regional carbon emissions per capita in the YRD urban agglomeration in 2018 by using the factor detection and interaction detection modules in the Geographical Detectors. The expression is as follows:

$$q = 1 - \frac{\sum_{h=1}^L N_h \sigma_h^2}{N \sigma^2} \tag{3}$$

where q is the dissimilarity factor, with a larger q indicating more spatially significant dissimilarity in the data; l is the number of variable categories; $h = 1, 2, \dots$, for a specific type; N_h and N denote the number of cells in category h and the entire region, respectively; σ_h and

σ are the variances of category h and the entire region, respectively [25].

Gini Coefficient

The Gini coefficient is one of the common indicators used internationally to measure the income disparity between residents of a country or region, and was also often used by economists, geographers and others to characterize regional differences in a given economic or social indicator. In this paper, the Gini coefficient is used for evaluating the the changes of regional differences in carbon emissions per capita in the YRD urban agglomerations during the study period. Generally, the common value of 0.4 was used as a "critical value" for emission differences. A Gini coefficient between 0.2 and 0.3 translated into "relatively average"; between 0.3 and 0.4 translated into "reasonable"; between 0.4 and 0.5 translated into "large"; and above 0.5 translated into "highly uneven" [26]. The formula for calculating the Gini coefficient is as follows:

$$GiNi_c = 1 - \sum_{i=1}^n(p_i - p_{i-1})(E_i - E_{i-1}) \tag{4}$$

where $GiNi_c$ denotes the Gini coefficient of per capita carbon emissions, p_i denotes the cumulative population share of a city in a given year, and E_i denotes the cumulative emission share of a town in a given year.

Results

Urban Agglomeration and Carbon Emissions

As shown in Fig. 2, regarding per capita carbon emissions of the YRD urban agglomeration from 2006 to 2018, 2016 appears to be a turning point, before which "slow and subsequently sharp" continuous growth is evident, and after which rapid growth is evident. From 2006 to 2018, per capita carbon emission in the YRD urban agglomeration increased from 1.68 to 1.99 t/person, with 9.2% average annual growth rate; the growth rate sharply increased from 2016 to 2018, i.e., average annual growth rate of 29.9%.

Following the "one city and three provinces" regional division, the proportion of carbon emissions in each district and county was calculated to reveal the regional differences. From 2006 to 2018, Jiangsu Province accounted for approximately 40% of the carbon emissions in the YRD urban agglomeration, while being the main carbon source in the region. In contrast, due to the significant adjustment of industrial and energy structures, Shanghai's carbon emission ratio declined rapidly from 28.09% in 2006 to 13.00% in 2018, i.e., a drop of 53.7%. The carbon emissions of Anhui Province exhibited a small annual increasing trend, from 9.43% in 2008 to 14% in 2018. During the study period, with the rapid improvement of the urbanization level in Zhejiang Province, the

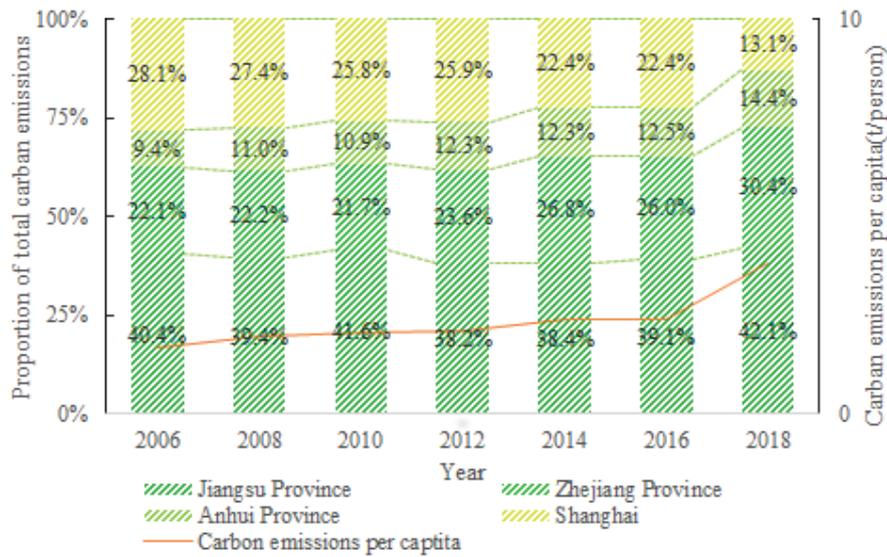


Fig. 2. Changing trend of per capita CO₂ emissions and regional total carbon emissions in the Yangtze River Delta urban agglomeration.

permanent population increased to 57.37 million, which along with the rapid development of energy-intensive industries and the rapid growth of energy consumption, led to an annual increase in carbon emissions. The proportion of carbon emissions increased by eight percentage points during the study period. Overall, Jiangsu Province accounted for the largest proportion of carbon emissions of the YRD urban agglomeration, followed by Zhejiang Province. With the change in the urban development stage, Shanghai accounted for a similar proportion of carbon emissions as that of Anhui Province.

This study used the Gini coefficient to measure the difference in carbon emission levels per capita among cities in the YRD urban agglomeration (Fig. 3). According to international conventions, a Gini coefficient below 0.2 indicates a “highly/absolute average” regional distribution of carbon emissions; between 0.2 and 0.3, it is “relatively average”; between

0.3 and 0.4, it is “reasonable”; between 0.4 and 0.5 indicates a “large gap”; and above 0.5 indicates a “highly uneven” regional distribution. 0.4 is the common “critical value” for emissions differences. From the perspective of urban agglomerations, the Gini coefficient of per capita carbon emissions in the YRD urban agglomeration decreased from 0.52 in 2006 to 0.30 in 2018 and the differences in per capita carbon emissions gradually narrowed. Regarding the provinces, the Gini coefficients of Jiangsu, Zhejiang, and Anhui Provinces exhibited downward trends during the study period, while remaining below 0.30. The Gini coefficient of per capita carbon emissions in Anhui Province fluctuated significantly, while exhibiting three increases. The Gini coefficient peaked in 2008; it subsequently declined rapidly in 2016, while falling below 0.4, and lower than the average level of the YRD urban agglomeration after 2017. The Gini coefficient of per capita carbon emissions in Jiangsu Province

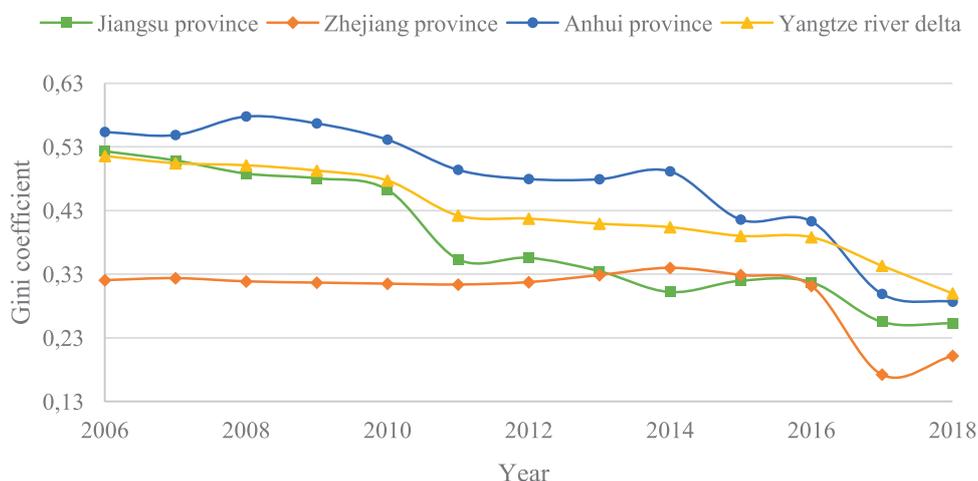


Fig. 3. Changes in the Gini coefficients of per capita CO₂ emissions of three provinces and one city in the Yangtze River Delta.

exhibited an obvious downward trend with relatively large fluctuations; it was lower than the average level of the YRD urban agglomeration after 2008 and lower than the 0.4 critical value after 2010. The Gini coefficient of urban per capita carbon emissions in Zhejiang Province did not exceed the 0.4 critical value during the study period; it fluctuated slightly from 2006 to 2012, while thereafter, it increased slightly before eventually sharply declining in 2017.

Spatiotemporal Distribution Characteristics of per Capital Carbon Emissions

Spatial Distribution Analysis

From 2006 to 2018, per capita carbon emissions of the YRD urban agglomeration increased to some extent, and their spatial distribution gradually stabilized. There was significant north-south divergence and spatial aggregation, with the Yangtze River being the dividing line (Fig. 4). High per capita carbon emissions were mainly concentrated in Shanghai, Nanjing, Suzhou, and other towns along the Yangtze River, as well as in developed cities in various provinces. This may be due to the high level of economic development in these cities, the large number of permanent residents, the rapid growth of energy-intensive industries, the expansion of the scale of energy consumption, and the irrational energy structure. Shanghai, Nanjing,

Hangzhou, Suzhou, Wuxi, and other cities with high urbanization levels exhibited relatively high per capita carbon emissions, and so did neighboring towns around them. Therefore, with further improvements in regional economic development levels and population accumulation in the future, per capita carbon emission levels in these regions will continue to rise, and the “core-edge” effect of carbon emissions will become increasingly prominent without significant optimization of the energy consumption structure. Overall, the low-carbon economy of developed cities is pivotal regarding the green transformation of the surrounding areas and the ultimate goal of energy conservation and emission reduction in China.

Agglomeration Characteristics Analysis

In this study, Moran’s *I* was calculated to reflect the spatial autocorrelation of per capita carbon emissions in the YRD urban agglomeration and to characterize the local spatial agglomeration characteristics (Table 1). According to the calculation, the fluctuation range of Moran’s *I* of per capita carbon emissions in the YRD urban agglomeration was 0.251-0.850, with *Z* values being greater than 1.96 and *P* values being lower than 0.05. From 2006 to 2018, Moran’s *I* passed the 95% confidence level. According to the results, per capita carbon emissions in the YRD urban agglomeration exhibited an obvious positive global spatial correlation

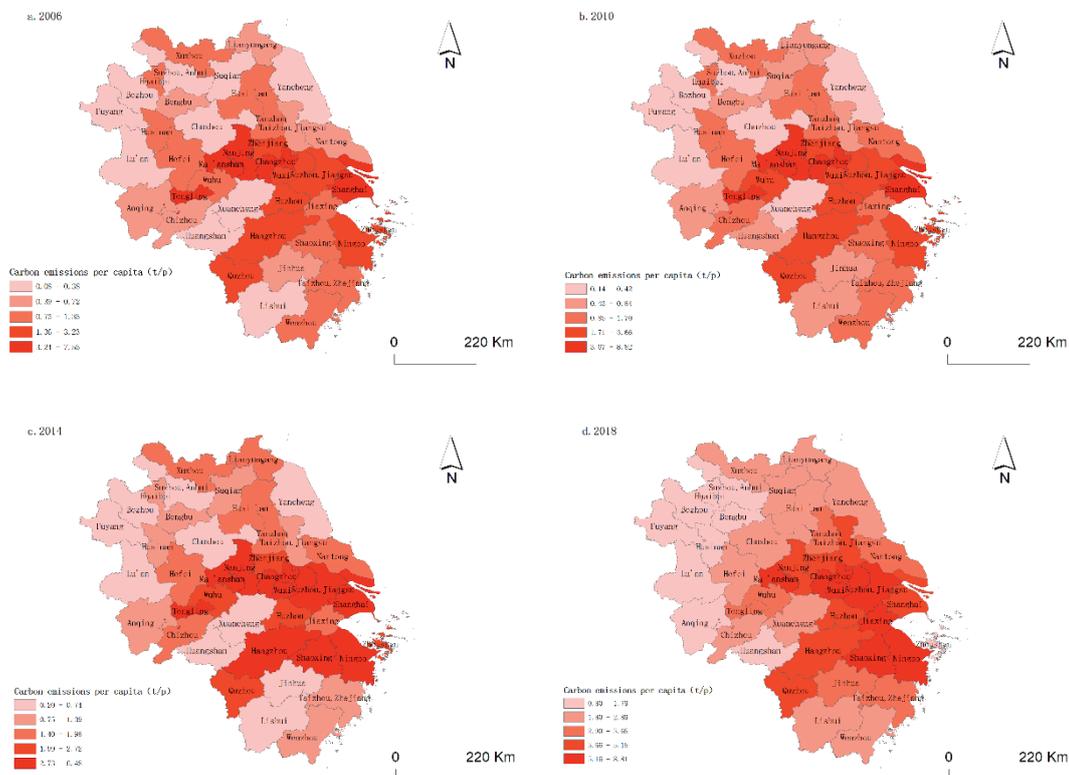


Fig. 4. Spatiotemporal evolution of per capita CO₂ emissions in the Yangtze River Delta urban agglomeration.

Table 1. Calculation results of the global Moran's *I* of the Yangtze River Delta urban agglomeration.

Year	Moran's <i>I</i>	Z values	P values
2006	0.2829	2.9013	0.0037
2007	0.3024	3.0900	0.0020
2008	0.3613	3.5800	0.0003
2009	0.3398	3.4483	0.0006
2010	0.3274	3.3370	0.0008
2011	0.2504	2.4646	0.0137
2012	0.3146	3.0198	0.0025
2013	0.3085	2.9646	0.0030
2014	0.2965	2.8532	0.0043
2015	0.4308	4.0273	0.0001
2016	0.4706	4.3790	0.0000
2017	0.8494	7.7905	0.0000
2018	0.8439	7.7161	0.0000

in geographical space. Moran's *I* of per capita carbon emissions in the YRD urban agglomeration showed that the change process experienced three stages: (1) Fluctuation and rise stage from 2006 to 2010; Moran's *I* increased from 0.283 in 2006 to 0.327 in 2010, indicating that per capita carbon emission levels of

41 cities of the YRD increased. (2) Stable increase from 2011 to 2014; during this period, Moran's *I* fluctuated little after falling to 0.25 in 2011. (3) Sharp rise from 2015 to 2018; it peaked at 0.85 in 2017, indicating that the spatial dependence of the YRD urban agglomeration was strong and that all regions were relatively close. Overall, Moran's *I* of per capita carbon emissions of 41 cities of the YRD revealed a "rising, decreasing, stable, and sharply rising again" trend; it is therefore concluded that the overall spatial pattern of per capita carbon emissions in 41 cities of the YRD has not yet reached a steady state and is still within a relatively wide fluctuation range.

The LISA agglomeration map was used for analyzing the local spatial accumulation and dispersion of per capita carbon emissions in the YRD urban agglomeration. 2004, 2010, 2014, and 2018 were the typical years for thorough analysis. In general, the spatial agglomeration types of per capita carbon emissions in the YRD urban agglomeration were roughly fixed (Fig. 5). High-high (HH) and low-low (LL) aggregations were the main local spatial autocorrelation types. In addition, the number of LL-clustering cities was gradually increasing, while the number of HH-clustering cities was relatively decreasing; this finding is similar to the results of spatial clustering distribution of per-capita carbon emissions of other prefecture-level towns [27] and per capita carbon emissions of provinces [28-30].

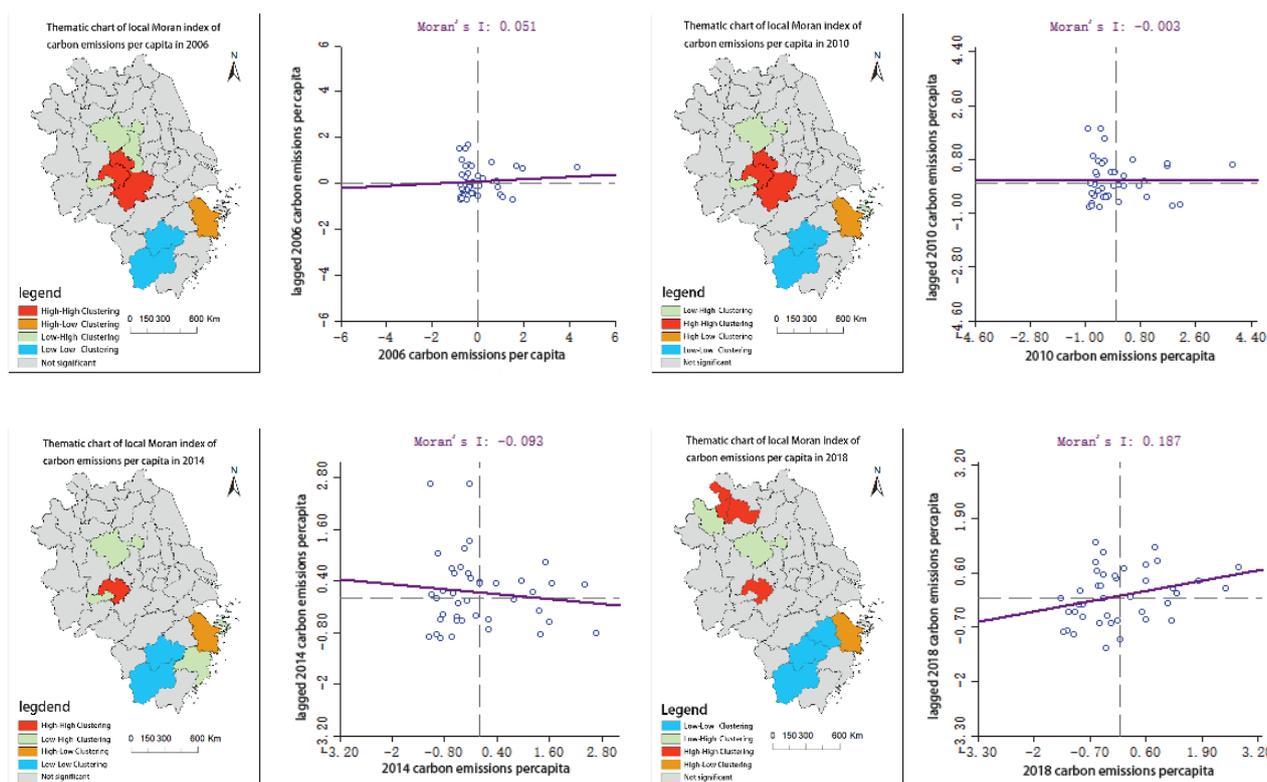


Fig. 5. LISA cluster map and Moran's *I* scatter plot of per capita CO₂ emissions in the Yangtze River Delta urban agglomeration. Note: Y is carbon emissions per capita; X is a candidate factor

As shown in Fig. 5, HH-clustering cities gradually moved northwest. The original clustering areas (i.e., Wuhu, Maanshan, and Hefei) disappeared and were mainly distributed in Huaibei and Suzhou during the later period. In contrast, LL-clustering areas remained unchanged and were primarily distributed in Lishui, Jinhua, Shaoxing, and Ningbo. The main reason for this may be that cities such as Wuhu and Hefei are undergoing industrial transformation and upgrading. In the latter stages of industrialization or urbanization, cities have entered the development stage from scale expansion to quality improvement. With ecological environment optimization and industrial layout management, carbon emissions have been controlled to a certain extent. During the “13th Five-Year Plan” period, Lishui and Jinhua have always adhered to the low-carbon development strategy and closed a large number of high-energy-consuming enterprises, which were the main reasons for the low per capita carbon emission level here. However, because Suzhou, Huaibei and other northern Anhui cities have abundant coal resources and developed transportation, they have undertaken many high-energy-consuming industries transferring from Jiangsu and Zhejiang Province, making this area a HH-clustering area. Generally, the spatial and temporal structures of per capita carbon emissions from 2006 to 2018 exhibited relatively stable spatial correlations and relatively stable states.

Driving Forces of per Capita Carbon Emissions

Geographical Detectors

Based on previous research results and the characteristics of the YRD urban agglomeration, eight

specific factors that may influence per capita carbon emissions in the region were selected: total social sales (X1), gross industrial product (X2), residential vehicles (X3), road length (X4), social electricity consumption (X5), construction land (X6), parkland (X7), and urbanization rate (X8) (Fig. 6). The variance inflation factor (VIF) for each influencing factor was then calculated to test for multicollinearity of the data, with the three factors of gross industrial product, road length, and urbanization rate passing the multicollinearity test. Additionally, the factors influencing the spatial heterogeneity of per capita carbon emissions were diverse.

Subsequently, geographic detectors were introduced to explore the explanatory power of spatial differentiation of the above three factors on per capita carbon emissions, where geographic detectors could be specifically divided into four categories, namely factor, ecological, interaction, and risk detectors. The results are presented in Table 2. The q values indicate the explanatory power of each factor for the spatial variance of attribute Y. A q value ranges between 0 and 1, and the closer it is to 1, the stronger the explanatory power of this factor on Y is; the closer it is to 0, the weaker the explanatory power of this factor on Y is. The p-values were significant.

As it can be seen in Table 2, the ranking of factors influencing carbon emissions per capita were X2>X8 >X4; X2 had the highest q value, indicating that, among all the variables, the gross industrial product is the most significant factor influencing per capita carbon emissions. However, it can also be seen that the factors influencing the spatial heterogeneity of per capita carbon emissions are diverse.

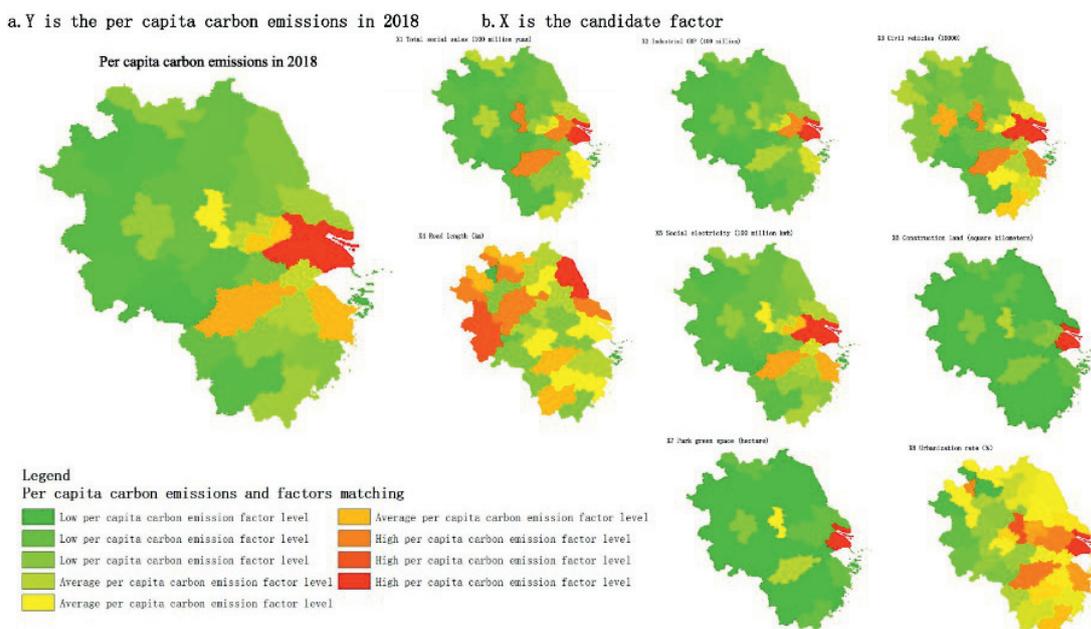


Fig. 6 Per capita carbon emissions and their driving factors in the Yangtze River Delta urban agglomeration.

Table 2. Factor-detector analysis results.

	X2	X4	X8
q statistic	0.927007	0.166170	0.644323
p value	0.000	0.000	0.000

Main Impact Factors

Three main factors influencing the spatial and temporal patterns of carbon emissions in the YRD urban agglomeration were screened by employing a geographical probe: gross industrial product, urbanization rate, and road length.

Gross industrial product was the most influential. Generally, GDP reflects a city's industrial sophistication, while per capita carbon emissions reflect the energy-use efficiency. In the middle and early stages of industrialization, an increase in gross industrial product significantly increases per capita carbon emissions, while in the middle and late stages of industrialization, with the large-scale intervention of energy-conservation and emission-reduction technologies, an increase in gross industrial product does not significantly increase per capita carbon emissions, and may even lead to no change or their slight decrease. Such results are generally consistent with the findings of Sun et al. [31]. Urbanization rate had the second highest impact. Urbanization can significantly contribute to the agglomeration of the population and other resources, while the agglomeration of the population can change local energy-use and transport patterns. In the case of the YRD urban agglomeration, during the middle and early stages of urbanization (i.e., urbanization rate below 60%), a large population concentration is inextricably linked to local industrialization, and an increase in the urbanization rate leads to a significant increase in per capita carbon emissions. In the middle and late stages of urbanization (i.e., above 60%), an increase in the level of urbanization is conducive to the economical and intensive use of resources, thereby delaying or even reducing per capita carbon emissions.

The influence of the road length is also evident. Road length is an important aspect of China's accelerated urbanization, and the concept of "building roads before getting rich" has materialized. According to statistics, the number of cars per 100 people in China was only 0.49 in 2000, but this figure had reached 17 by 2020. To meet the huge demand for private cars (mostly conventional energy vehicles), cities have strived to improve their road infrastructure, making them an important source of change in the regional per capita carbon emissions.

Discussion

This paper differs from previous studies in the following aspects. Firstly, since most carbon emission

studies only focus on the total amount of emissions, the effect of population is relatively neglected. Thus, in this paper we consider both total and per capita carbon emissions, and analyze the trends of per capita carbon emissions and total regional carbon emissions in the YRD urban agglomeration from 2006 to 2018 in detail. Secondly, in contrast to earlier studies using single influencing factor, we select eight factors from economic, social and environmental dimensions to carry out the analysis of the driving forces of carbon emissions per capita in the YRD urban agglomeration. Such a study might be more comprehensive and in line with reality. Thirdly, while previous relevant studies mainly focus on the trends and pattern measurement at China's national/provincial level, this study does empirical research at city level as a lot of China's carbon emissions are related to urban energy consumption. This work is also fundamental to achieve the national "carbon peaking and carbon neutrality" strategic goal.

In the "14th five-year plan" issued in 2022, the state council proposed to use as basis the primary national coal-based establishment, adhere to the "first established and subsequently broken", strictly and reasonably control the growth of coal consumption, grasp the clean and efficient use of coal, and vigorously promote energy conservation and emission reductions. To successfully implement pollution prevention and control, it is important to establish and improve a green, low-carbon, and circular-development economic system, promote the overall green transformation of economic and social development, and strive to achieve the goal of carbon peaking and carbon neutrality. Regarding the YRD urban agglomeration, while promoting the "double carbon" plan, we need to focus on the following issues: (1) Although the YRD urban agglomeration has a high level of economic development, its total energy consumption is still increasing, and the demand for economic development and achievement of low-carbon targets are mutually binding; (2) the YRD urban agglomeration contains 41 cities at the prefecture level and above, and their carbon emissions and energy-use efficiency vary greatly. (3) The YRD urban agglomeration possesses a large number of entities responsible for carbon emissions and energy use, making it impossible to compile accurate statistics on energy consumption and carbon emissions, and form a "carbon ledger" for local governments. To this end, this study proposes the following countermeasures.

The YRD urban agglomeration should be the first region to participate in the intelligent management of carbon emissions in China [32]. Taking the top-five cities with the carbon emissions in the region as pioneers, we can set up a carbon emission management platform and use an AI system to enter carbon emission data into the cloud and achieve real-time statistics and accurate tracking of energy consumption and carbon emissions throughout the region.

Managing the relationship between economic development and the "dual carbon plan". Promote the

integration of the YRD urban agglomeration, engage in multidimensional cooperation, actively build innovative collaborative governance mechanisms, accelerate the integrated ecological and green development of the YRD, and achieve simultaneous economic development and low carbon emissions.

Always maintain a firm grip on innovative technology to promote energy-conservation and emission-reduction strategies without wavering. We should promote the coordinated development of regional science and technology innovation and strengthen the effect of regional integration on emissions reduction. The governments of all cities should follow the 14th five-year plan for energy conservation and emission reduction, create a good environment for collaborative regional innovation and development regarding low carbon emissions, increase investment in green technology, encourage new cities to rationalize their industrial layout, and actively introduce existing technologies from core cities.

In conclusion, the low-carbon development of the YRD urban agglomeration needs a real-time, accurate, and scientific carbon emission management mechanism maintaining a strong grip on the sustainable implementation of the "double carbon" plan and also providing a reference for other urban agglomerations or regions in China in their quest to reduce energy consumption and emissions.

Conclusions

This study focused on 41 prefecture-level cities of the YRD urban agglomeration. First, it analyzed the changing trend of per capita carbon emissions in the YRD urban agglomeration. Second, it explored the spatial and temporal distribution characteristics and spatial agglomeration characteristics of per capita carbon emissions of the YRD urban agglomeration. Finally, it discussed the influencing factors of the evolution of per capita carbon emissions in the region by using a geographical probe. The main conclusions are as follows:

Per capita carbon emissions of the entire YRD urban agglomeration continuously increased from 2006 to 2018, with 2016 being a turning point. The share of carbon emissions in Jiangsu Province remained at around 40%; the share of carbon emissions in Anhui Province and Shanghai Municipality fluctuated and decreased; and the share of carbon emissions in Zhejiang Province increased slowly.

The Gini coefficient of per capita carbon emissions of the YRD urban agglomeration decreased from 0.52 in 2006 to 0.30 in 2018, while the Gini coefficient of per capita carbon emissions in cities in Anhui Province fluctuated more markedly with a large internal gap. The Gini coefficient of per capita carbon emissions in cities in Zhejiang Province did not exceed the 0.4

critical value during the study period, and the difference in carbon emissions was more reasonable; in Jiangsu Province and YRD, the level was the same, with a clear downward trend.

From 2006 to 2018, per capita carbon emissions of the YRD urban agglomeration exhibited a north-south divergence, with the Yangtze River being the dividing line, and the spatial distribution gradually stabilizing. There is a significant positive spatial correlation between per capita carbon emissions in urban agglomerations, but it has not yet formed a steady state, with high-high agglomerations gradually moving to the northwest, while low-low agglomerations remaining unchanged. The spatial and temporal patterns of carbon emissions in the YRD urban agglomeration and other important cities are of great value regarding promoting the achievement of China's energy-saving and emission-reduction goals at this stage and in the future.

Factor-detector analysis of per capita carbon emissions of the YRD urban agglomeration showed that the gross industrial product, urbanization rate, and road length were the three main factors affecting per capita carbon emissions. With the thorough implementation of the "innovation, coordination, green, openness, and sharing" development concept in the region, and the increasing efforts regarding economic transformation, low-carbon development, and energy structure optimization in each city, the increasing momentum of per capita carbon emissions of the YRD urban agglomeration has been initially curbed.

Based on the above conclusions, we can provide some valuable suggestions for policy makers regarding carbon emission reduction. An intelligent carbon emission management system should be set up quickly in the YRD urban agglomeration in order to control the whole process of carbon emissions accurately. Handle the relationship between economic development and the "carbon peaking and carbon neutrality" strategy, and accelerate its ecological and green development. Hold the strategy of innovative technology to promote energy saving and emission reduction without wavering, and increase investment in green technology and strengthen the effect of regional integration in emission reduction.

The trend of carbon emissions in the YRD urban agglomeration from rapid growth in the first decade of the 21st century to slow growth in recent years demonstrated China's low carbon development path to other countries and regions around the world. China has shown the world through its own practice that it is possible to change the old development model and follow a sustainable development path that leads to success. The results of the analysis of the driving forces also indicated that in the middle and late stages of urbanization, carbon emission reduction can be implemented from three following aspects: low carbonization of industrial development, low carbonization of lifestyle and low carbonization of energy structure.

Acknowledgments

This work was funded by the General Project of Philosophy and Social Sciences Research of Jiangsu Province (2019SJA1451) and Nantong Science and Technology Plan Project (JC2020172).

Conflict of Interest

The authors declare no conflict of interest.

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