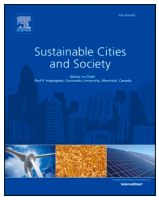
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Spatiotemporal evolutionary characteristics and driving forces of carbon emissions in three Chinese urban agglomerations

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ABSTRACT

Assessing carbon emissions in urban agglomerations has emerged as a pivotal step towards achieving carbon neutrality. In this study, panel data from 75 cities within the three largest urban agglomerations in China—the Yangtze River Delta (YRD), Beijing-Tianjin-Hebei (BTH) region, and Pearl River Delta (PRD)—were constructed to analyse the spatiotemporal evolution of carbon emissions from 2005 to 2020. An indicator system was established, and the Spatial Durbin Model (SDM) was used to investigate the driving forces of carbon emissions. The findings revealed a gradual increase in carbon emissions within these agglomerations, with a notable shift in their spatial distribution from metropolitan areas to broader urban agglomerations, exhibiting significant spatial correlation. Additionally, variations in carbon emissions were observed across different development stages. The SDM indicated that several factors, such as economic conditions, industrialization levels, and population size, influenced the carbon emissions of urban agglomerations. Nevertheless, the impact of these driving factors on carbon emissions was not constant and could be altered by other elements, including green technologies and governmental policies, indicating a decoupling effect between economic growth and carbon emissions. The insights from this study can assist policymakers in formulating strategies to curb carbon emissions and foster sustainable development.

1. Introduction

In recent years, global warming has been driven primarily by greenhouse gas (GHG) emissions, especially carbon dioxide (CO_2) emissions resulting from the extensive energy consumption associated with global urbanization processes (Acheampong et al., 2021; Bai et al., 2019a; Oudes & Stremke, 2018; Padro et al., 2020). The International Energy Agency reported that global carbon emissions rose from 23.2 billion tons in 2000 to 36.8 billion tons in 2022, an increase of approximately 58 %. These figures underscore the urgency and significance of reducing carbon emissions to address global climate change.

As the largest developing country, China has experienced a significant increase in emissions. In 2020, carbon emissions in the Asia-Pacific region accounted for more than half of the global total, reaching 52 %, with China contributing 30.7 % of this amount, highlighting the necessity of its energy conservation and emission reduction strategy (Auffhammer & Carson, 2008). Studies have indicated that approximately 85 % of China's carbon emissions originate from urban areas (Deng & Bai, 2014), leading to a more concentrated spatial distribution of emissions (Y. Yu et al., 2023). At the 2015 United Nations Climate Change Conference, the Chinese government announced its commitment to peak carbon emissions by 2030 and to strive for carbon neutrality by 2060 (Y. Zhao et al., 2022). These objectives emphasize China's urgent role and strategic position in reducing global carbon emissions.

Currently, the urban agglomerations in the Yangtze River Delta (YRD), Pearl River Delta (PRD), and Beijing-Tianjin-Hebei (BTH) regions have significant impacts on both the Chinese and global economies. These three urban agglomerations have consistently driven China's economic development, collectively accounting for nearly 50 % of China's national GDP. Additionally, the environmental and climate change issues in these areas are becoming increasingly severe (K. Liu

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et al., 2020). Hence, these urban agglomerations play a crucial role in China's energy conservation and emission reduction strategies. The rapid population growth and escalating resource demands in these regions have exerted substantial pressure on the ecological environment of Chinese cities (Bai et al., 2019b; Fang & Lin, 2009). Consequently, China cannot rely solely on future CO_2 emission reductions through improved energy efficiency and industrial structure optimization (S. Wang et al., 2017). The strategic significance of these three urban agglomerations in achieving China's carbon reduction and sustainable development goals is undeniable. Not only are they engines of economic growth, but they are also key to regional sustainable development. With the steady advancement of regional development strategies, such as new urbanization, regional integration, and urban agglomeration construction, China's economy is increasingly focusing on coordinated development with environmental improvement and social progress (Y. Wang, Yin et al., 2022). Thus, it is actively responding to global climate change by effectively controlling and reducing carbon emissions (Fu et al., 2020).

2. Literature review

Previous research on the carbon emissions of urban agglomerations has focused primarily on two issues: the spatiotemporal patterns of carbon emissions and their driving forces.

2.1. Spatiotemporal patterns of carbon emissions in urban agglomerations

Research on the spatiotemporal evolutionary characteristics of carbon emissions in urban agglomerations can be used to understand and predict carbon emission trends and to provide strategic support for carbon emission management and reduction. Studies on the spatiotemporal pattern of carbon emissions have focused mainly on the following three issues: 1) spatiotemporal evolutionary characteristics, 2) feature condensation, and 3) assessment methods.

Previous research on spatiotemporal evolution has shown that the spatial distribution of carbon emissions in urban agglomerations is geographically distinct and that carbon emissions are characterized by significant spatial heterogeneity rather than a uniform distribution. This implies that emissions vary markedly across different areas within these urban clusters. Such heterogeneity mirrors disparities in the economy (Q. Yu et al., 2022), societal dynamics (Yin et al., 2023), urban morphologies (Falahatkar & Rezaei, 2020), functional roles (F. Zhao et al., 2023), and infrastructural compositions within specific regions (Dong & Li, 2022). These determinants encompass resources and the spatiotemporal distribution of socioeconomic activities, which influence the spatial patterns of carbon emissions in urban agglomerations. For example, some scholars have found an inverted U-shaped relationship between the urban spatial structure and energy use efficiency, which varies across different regions (C. Xu et al., 2021).

In terms of feature condensation, as the urbanization process continues to advance, urban agglomerations are progressively replacing individual cities, becoming the primary regional units of global competition and specialization (J. He et al., 2017; Y. Huang et al., 2020). Throughout this transformation, interactions between cities have led to differentiated spatial characteristics of urban agglomerations. The rapid development of urban agglomerations has intensified energy consumption and carbon emissions (Xing et al., 2022). Consequently, much attention has been paid to delineating the spatial carbon emissions of different urban agglomerations, which can help guide sustainable development (Auffhammer, 2003; J. He et al., 2017; Y. Wang et al., 2019).

In addition to the issues above, scholars have applied different methods/models, such as the geographically weighted regression (GWR) model (K. Liu et al., 2022; Y. Wang, Niu et al., 2022) (Liang et al., 2019; B. Wang et al., 2021), spatial lag model (SLM), spatial error model (SEM) (Sun et al., 2022), and spatial Durbin model (SDM) (X. Huang & Tian, 2023), to assess urban carbon emissions. The GWR model is effective at revealing geospatial heterogeneity, shedding light on distinct variable relationships across various locations. The SLM efficiently handles spatial dependency within spatial data by discerning interactions among adjacent areas. The SEM addresses spatial autocorrelation issues caused by correlated errors, thus enhancing the precision of estimates. Among these models, the SDM has several distinct advantages. First, its holistic approach allows it to capture not only the spatial lag effects of the dependent variable but also the spatial dynamics of explanatory variables, offering a more comprehensive perspective than the SLM and SEM. Second, the SDM excels in detecting intricate spatial interactions and nonlinear relationships, proving itself invaluable in interpreting the complex spatial dynamics inherent within urban clusters. Third, in contrast to the GWR model, the SDM provides a nuanced parametric characterization of spatial effects, yielding more reliable estimates across diverse research contexts. Moreover, the inherent interpretability of the model, as it delineates both the direct and indirect impacts of the explanatory variables, furnishes deeper insights that are pivotal for policy recommendations. Its precision in parameter estimation, especially under scenarios where explanatory variables exhibit spatial effects, enhances its overall accuracy (Elhorst, 2010; B. Li & Wu, 2017; Tiefelsdorf & Boots, 1995).

2.2. Driving factors of carbon emissions in urban agglomerations

Notably, the carbon emissions of urban agglomerations are affected by various factors, such as urban industry composition, socioeconomic levels, urban spatial form, and even governmental policies.

In terms of urban industry composition, scholars have found that the composition, developmental trends, and spatial distribution of industries within urban areas directly influence their carbon emissions (Y. Wang et al., 2020). For instance, in the manufacturing sector, heavy industries such as steel, chemical, and petroleum processing typically generate more carbon emissions than do sectors within the service industry, including finance, education, healthcare, and tourism (Wu et al., 2021). With technological advancements, trade liberalization, and evolving industrial structures, several industries have enhanced energy efficiency in their production processes. These improvements are largely attributable to technological progress, which not only optimizes energy use but also facilitates the dissemination of energy-efficient technologies through increased trade openness. Consequently, this synergy between technology and trade has played a pivotal role in reducing overall energy consumption (Alam & Murad, 2020). Furthermore, the spatial distribution of industries affects the carbon footprint of transportation and logistics, consequently impacting the carbon emissions of urban agglomerations (Elinwa et al., 2021). To conduct in-depth research on the spatial characteristics of carbon emissions in specific industries, scholars have also analysed the driving factors of carbon emissions in the transport and power industries (Y.-Y. He et al., 2020). Additionally, Ma (Ma et al., 2019) identified a decoupling state between the carbon intensity of the commercial building sector and the economic development of the service industry. By analysing the environmental Kuznets curve relationship between carbon emissions and the economic growth of the commercial building sector, Ma observed an inverted U-shaped decoupling phenomenon in various urban areas. The growth of this decoupling effect is credited to the rapid advancement of energy efficiency projects within the commercial building sector over the past decade.

In terms of socioeconomic levels, scholars have found that real GDP per capita (Jalil & Mahmud, 2009; Zaidi & Saidi, 2018), the urbanization rate (Q. Xu et al., 2018), the proportion of the tertiary industry (Nwani et al., 2023; A. Zhang & Deng, 2022), the proportion of renewable energy sources (Usman & Radulescu, 2022) and fixed asset investment (Xiao et al., 2022) have great impacts on carbon emissions. Among them, GDP per capita has the greatest impact, and the urbanization rate is the most capable of inhibiting an increase in carbon emissions (Shuai et al., 2018). This finding can be attributed to the fact

that the development approach in many developing countries is extensive, relying predominantly on increasing inputs such as labour and scaling up investments to enhance production. Consequently, substantial growth in per capita GDP leads to significant increases in individual incomes, thereby driving a greater demand for energy-consuming products (Shen et al., 2017; Y.-J. Zhang & Da, 2015). Moreover, other studies have posited that energy prices influence residential energy choices, subsequently impacting carbon emissions (Ali et al., 2019).

In terms of urban spatial form, scholars have found that population density, the urban structure and the undesirable aggregation of resources in cities promote carbon emissions (Chiquetto et al., 2022). Further studies indicate that a compact urban structure can enhance energy utilization efficiency, leading to a reduction in per capita carbon emissions (Fang et al., 2015). In contrast, urban sprawl, fragmentation, and complexity in urban form have been linked to increased carbon dioxide emissions (Z. Li et al., 2022).

In terms of governmental policies, studies have shown that urbanization in some developing countries is unsustainable and that there is an urgent need to formulate carbon-reducing planning policies (Dhakal, 2009; Zhou et al., 2021). Such research posits that governmental policies can play a pivotal role in guiding effective carbon emission reductions (Z. Liu et al., 2022). Thus, it is imperative to manage urban land expansion and population density through urban planning and by employing urban planning measures to control emissions. The pursuit of a compact urban development model further aids in reducing carbon dioxide emissions (S. Wang et al., 2017). Furthermore, in more specialized research areas, some scholars have observed a positive correlation between a government's commitment to achieving carbon neutrality and a city's efforts to mitigate and adapt to carbon emissions (Salvia et al., 2021). Additionally, if governments were to further encourage and subsidize green energy sources, they would greatly assist in addressing the challenges of environmental degradation (Sen & Ganguly, 2017). Finally, to bolster the advancement of renewable and clean energy, policymakers should prioritize and refine policies related to the financial system (Ramzan et al., 2023).

In summary, while existing studies have contributed some insights into the socioeconomic and policy mechanisms impacting carbon emissions, they often focus on systems or elements in isolation, thus lacking a holistic understanding of the integrated role that these mechanisms play in shaping urban carbon emissions. Indeed, there are still numerous research questions that emerge at the intersection of spatiotemporal patterns and carbon emissions, particularly in urban agglomerations. These complex systems, characterized by interwoven economic, social, ecological, and spatial elements, demonstrate intricate interactions and effects on their carbon emission mechanisms. Specifically, in urban agglomerations experiencing rapid urbanization, socioeconomic systems and governmental policy mechanisms not only shape spatial configurations but also exert significant influences on carbon emissions. These influences manifest themselves across time and space, forming unique spatiotemporal patterns. However, a gap remains in the specificity of existing research at the regional level, as much of the focus has been on single cities or national scales, with urban agglomerations as an intermediate scale that is often overlooked. Additionally, comparative studies examining the mechanisms of carbon emission influences across different urban agglomerations are scarce and warrant further attention.

The innovation of this paper lies in its analysis of not only the heterogeneity of carbon emissions within urban agglomerations but also the exploration of the differences and causes of carbon emissions between different urban agglomerations. By employing the SDM, this study accurately captures the spatial effects of the dependent variable, offering a more comprehensive perspective to understand the complex dynamics of carbon emissions in urban agglomerations. This study not only enriches our understanding of the carbon emission mechanisms in urban agglomerations but also provides new insights for formulating more effective regional carbon reduction strategies. Therefore, by thoroughly analysing the similarities and differences in carbon emissions among different urban agglomerations, as well as the comprehensive impact mechanisms of carbon emissions in relation to population, the economy, urbanization, and environmental policies, and their spatiotemporal evolution, this paper aims to provide a more comprehensive reference for policy formulation and management. On this basis, this study seeks to answer the following two detailed questions:

1) What are the key spatiotemporal patterns characterizing the evolution of CO_2 emissions within and between urban agglomerations?
2) What specific aspects constitute the interrelationships between the spatiotemporal patterns of CO_2 emissions in urban agglomerations and factors such as socioeconomic and policy mechanisms, and how do these relationships changes?

3. Data and methods

3.1. Study area

This paper evaluates the three largest urban agglomerations in China as case studies: the YRD, PRD, and BTH urban agglomerations (Fig. 1). The YRD is located in the eastern coastal region of China and includes 4 provincial capitals and 37 prefecture-level cities, and it has a land area of 211,700 km^2. In 2022, the YRD accounted for 12.5 % of China's total population, and its GDP reached 29.03 trillion yuan. This amount represents approximately 24 % of the nation's overall GDP, even though the area occupies only 2.3 % of China's total landmass. The PRD is located in the southern coastal region of China and includes 9 cities, such as Guangzhou and Shenzhen. It accounts for 0.57 % of China's land area but accounted for 8.8 % of China's GDP and 4.5 % of its population in 2020. The BTH region is located in northern China and includes 11 cities, including Beijing and Tianjin. With 2.3 % of the China's land area, it accounts for 7.8 % of the population and 8.5 % of its GDP. By 2021, these three urban agglomerations accounted for 25.13 % of the Chinese population and 37.40 % of GDP, with only 5 % of China's land area. The rapid expansion of urban areas and the sharp increase in carbon emissions have seriously affected the sustainable development of urban agglomerations.

3.2. Data sources

The data employed in this article encompassed regional socioeconomic attributes, government work reports and urban planning data, as well as urban carbon emission data. The regional socioeconomic attribute data were primarily derived from the "China City Statistical Yearbook" and other provincial and municipal statistical yearbooks covering the years from 2005 to 2020. These data sets included total economic output (T-GDP, in ten thousand RMB), per capita GDP (P-GDP, in ten thousand RMB), the level of social consumption (GRSCG, in ten thousand RMB), the degree of industrialization (SI-GDP, percentage), the service industry level (ST-GDP, percentage), population density (PD, people per square kilometre), population size (PS, in ten thousand), and the urbanization rate (UBR, percentage). To mitigate the impact of dimensional disparities on the analysis, max-min normalization was applied to these data.

Government work reports and urban planning data were sourced from official texts and annual reports published on the websites of various government levels. They encompassed indicators such as transport planning (RA, in ten thousand square metres), public transport (NBO, number of vehicles), transport prosperity (RA-P, in square metres), urban land use (BA, in square kilometres), environmental planning (IEP-GDP, percentage), environmental regulation (REV-GWR, percentage), the number of green technologies (Green-TP), the level of green technologies (Green-TL, percentage), and the capacity for government intervention (FE-GDP, percentage).

The urban carbon emission data integrated the database of the China

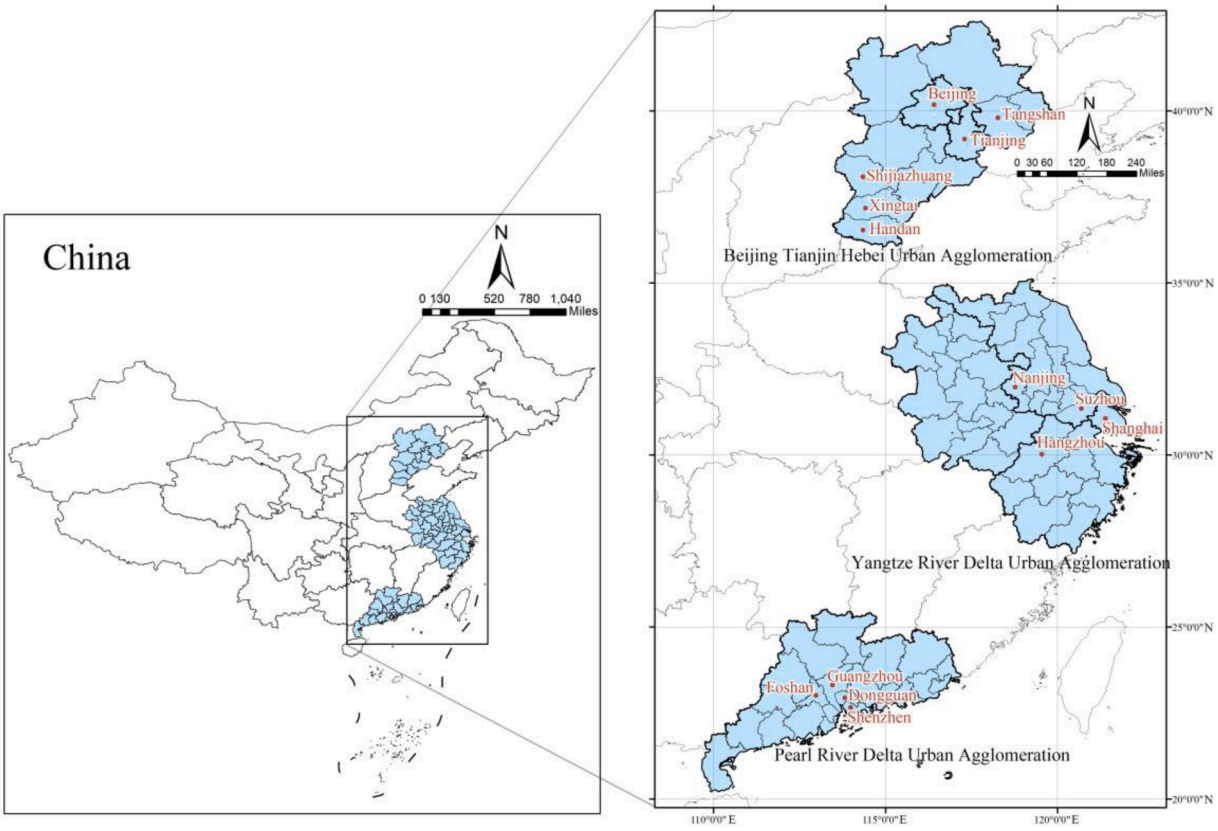


Fig. 1. The locations of the YRD, PRD and BTH urban agglomerations and their case cities.

City Greenhouse Gas Working Group (CCG) (accessed on June 1, 2023, at http://www.cityghg.com/toCauses?id=4) with various other official urban-level data sources. Additionally, the data included information gathered from field research analyses, data obtained from relevant government departments, and interviews with government officials. The comprehensive use of these data sources provided an extensive and in-depth perspective for exploring and analysing the dynamics and factors influencing carbon emissions in major Chinese urban agglomerations. Notably, the carbon emission data in this study encompassed Scope 1 and Scope 2 emissions within Chinese cities. Scope 1 emissions refer to all direct emissions within a city's administrative boundaries, while Scope 2 emissions pertain to indirect emissions resulting from a city's purchase of electricity from external sources. The foundational urban data integrated three primary sources: the CHRED 3.0 database; various official data at the city level, including statistical yearbooks, government documents, and research reports; and data acquired by the CCG through field surveys, interviews, telephone consultations, and correspondence with relevant departments (China City Greenhouse Gas Working Group., 2022; China City Greenhouse Gas Working Group 2022). The descriptive statistical tables for the data on the three urban agglomerations are shown in Tables 1,2,3.

3.3. Methodology

The methodology of this study was structured into three interconnected stages, as illustrated in Fig. 2. The first stage, data

Table 1
Descriptive Statistical Table for the BTH Region.

Variable	Abbreviation	Unit of measurement	Max	Min	Average	Standard deviation
Carbon emissions	CO_2	10,000 tons	33,487	939	7844.938	6459.85
Economic aggregate	T-GDP	RMB 10000	361,030,000	3,602,892	43,685,567.202	60,628,897.236
Economic level	P-GDP	RMB 10000	164,900	9947	43613.584	30337.994
Social consumption level	GRSCG	RMB 10000	150,636,524	1,178,961	16,448,268.034	24,073,027.634
Industrialization level	SI-GDP	%	62.1	15.83	45.425	10.157
Service industry level	ST-GDP	%	83.87	24.44	43.756	13.15
Population distribution	PD	p/km^2	931.691	91.35	548.822	231.555
Population size	PS	ten thousand	2195	288	809.944	464.341
Urbanization rate	UBR	%	87.55	29.745	53.582	14.922
Transport planning	RA	10000 m^2	17510	371	3309.029	3671.42
Public transport	NBO	Vehicle	25624	208	3806.639	5981.642
Transport prosperity	RA-P	m^2	31.708	5.26	15.672	4.102
Urban land use	BA	km^2	1469	35	266.731	371.173
Environmental planning	IEP-GDP	%	0.027	0.005	0.014	0.004
Environmental regulation	REV-GWR	%	0.008	0.001	0.004	0.001
Number of green technologies	Green-TP		24051	2	1015.673	3357.601
Level of green technologies	Green-TL	%	0.303	0.049	0.142	0.045
Capacity for government intervention	FE-GDP	%	0.402	0.056	0.159	0.064

Table 2
Descriptive Statistical Table for the PRD Region.

Variable	Abbreviation	Unit of measurement	Max	Min	Average	Standard deviation
Carbon emissions	CO_2	10000 tons	8343	164	2778.048	1894.799
Economic aggregate	T-GDP	RMB 10000	276,700,000	2,049,360	31,022,493.42	46,986,740.886
Economic level	P-GDP	RMB 10000	467,749	7488	52124.102	48354.012
Social consumption level	GRSCG	RMB 10000	95,515,699	234,796	11,797,014.318	16,697,850.629
Industrialization level	SI-GDP	%	65.6	25.17	46.672	8.584
Service industry level	ST-GDP	%	72.51	27.23	42.719	8.382
Population distribution	PD	p/km^2	3239.86	172.59	742.957	585.89
Population size	PS	ten thousand	1874	141.57	504.958	296.931
Urbanization rate	UBR	%	100	32.468	62.028	19.986
Transport planning	RA	10000 m^2	19147	58	2718.786	3814.786
Public transport	NBO	Vehicle	38728	56	2888.137	6586.247
Transport prosperity	RA-P	m^2	44.892	3.29	14.294	5.425
Urban land use	BA	km^2	1350	13	200.116	290.403
Environmental planning	IEP-GDP	%	0.026	0.006	0.014	0.004
Environmental regulation	REV-GWR	%	0.009	0	0.003	0.001
Number of green technologies	Green-TP		12343	0	492.881	1460.356
Level of green technologies	Green-TL	%	0.353	0	0.111	0.048
Capacity for government intervention	FE-GDP	%	0.401	0.054	0.139	0.066

Table 3
Descriptive Statistical Table for the YRD Region.

Variable	Abbreviation	Unit of measurement	Max	Min	Average	Standard deviation
Carbon emissions	CO_2	10000 tons	23790	170	4064.736	4247.022
Economic aggregate	T-GDP	RMB 10000	387,010,000	1,101,800	33,398,290.392	45,429,846.612
Economic level	P-GDP	RMB 10000	1,410,000	3761	58248.558	65322.715
Social consumption level	GRSCG	RMB 10000	159,325,030	397,220	12,628,245.154	17,768,650.341
Industrialization level	SI-GDP	%	74.73	23.97	48.37	8.375
Service industry level	ST-GDP	%	73.15	23.36	42.272	8.313
Population distribution	PD	p/km^2	2327.709	117.37	649.066	343.325
Population size	PS	ten thousand	2487	71	527.578	371.621
Urbanization rate	UBR	%	89.6	6.491	57.253	13.822
Transport planning	RA	10000 m^2	31012	138	2712.148	3075.085
Public transport	NBO	Vehicle	17985	70	1879.018	3013.611
Transport prosperity	RA-P	m^2	46.4	4.04	19.676	7.162
Urban land use	BA	km^2	1238	15	169.832	189.06
Environmental planning	IEP-GDP	%	0.023	0.001	0.011	0.004
Environmental regulation	REV-GWR	%	0.012	0	0.003	0.001
Number of green technologies	Green-TP		10612	0	643.816	1353.043
Level of green technologies	Green-TL	%	0.368	0	0.109	0.044
Capacity for government intervention	FE-GDP	%	1.485	0.055	0.15	0.08

preprocessing, involved compiling panel data from 75 cities within China's three major urban agglomerations spanning the years from 2005 to 2020. This stage focused on gathering data closely related to carbon emissions to provide a solid foundation for the subsequent analysis.

Following the data preprocessing stage, the study progressed to the second stage: the assessment of carbon emissions. This stage entailed a comprehensive analysis of the spatiotemporal evolutionary patterns of carbon emissions in urban agglomerations. It involved not only characterizing the changes in carbon emissions over time within a spatial context but also conducting spatial autocorrelation analysis. This stage was crucial for determining the spatial distribution patterns and spatial clustering of carbon emissions among urban agglomerations, providing insights into the geographic dynamics of emission trends.

The third and final stage was the impact mechanism analysis. In this stage, a comprehensive framework for evaluating carbon emissions was established by constructing an indicator system. This system integrated carefully selected indicators from the economic, social, and policy domains. With this framework in place, the study then applied spatial correlation models and the SDM to analyse and elucidate the complex mechanisms influencing carbon emissions in urban agglomerations. This sequential approach ensured a systematic exploration of carbon emissions, from data collection and pattern identification to in-depth mechanism analysis.

3.3.1. Carbon emission assessment and analysis

3.3.1.1. Spatial Durbin model (SDM). The conventional spatial econometric models include the SLM, SEM, and SDM. Compared with ordinary panel models, the SLM increases the spatial lag factor of the dependent variable, while the SEM increases the spatial lag factor of the error term. Compared with the SLM, the SDM increases the spatial lag term of the independent variable and considers the spatial spillover effects of the independent and dependent variables to avoid biased results caused by missing variables. The specific estimation form of this article needs to be determined by the following test results: the construction of a SDM is preliminarily determined through the Lagrange multiplier (LM) test results; the Hausman test clearly indicates the addition of fixed effects to the model; further verification through the Wald test and likelihood ratio (LR) test confirms that the data in this article are not suitable for constructing an SLM and SEM, and the SDM is the optimal choice. The SDM can be expressed as follows:

$$Y = \rho Wy + X\beta + \tau W\varepsilon + \mu \tag{1}$$

where Y is the dependent variable, which is urban carbon emissions; ρ represents the spatial lag coefficient; W represents the spatial weight matrix; Wy is the spatial lag dependent variable; and X represents the explanatory variable, which is an indicator of each type of factor. β represents the explanatory variable coefficient; τ represents the spatial error coefficient; ε represents the error term; and μ represents the

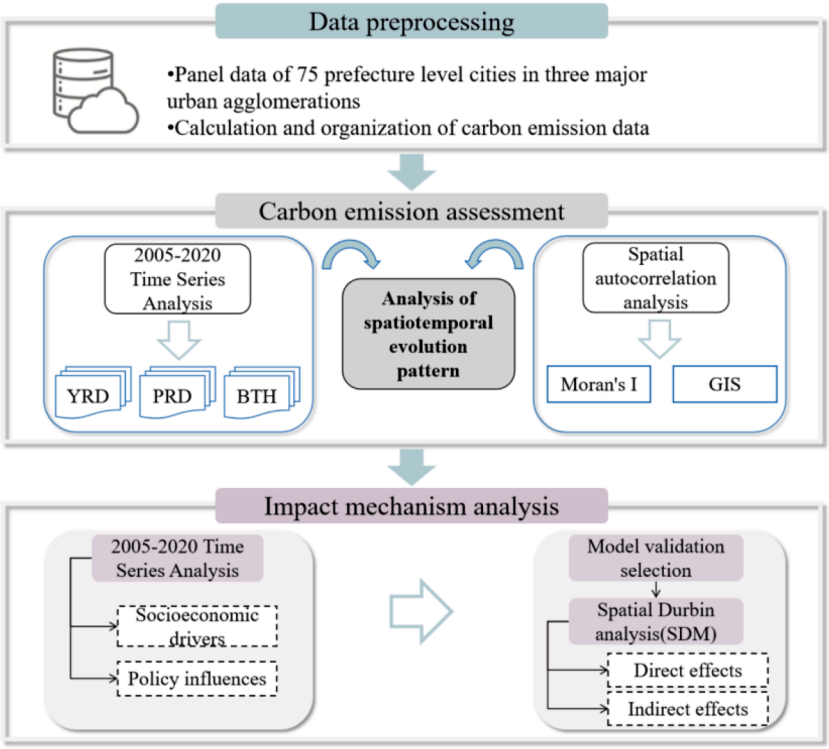


Fig. 2. Flowchart of the data and analysis.

disturbance term.

This paper primarily focuses on the mutual influences between geographically adjacent cities within urban clusters; thus, a contiguity matrix was selected as the spatial matrix for this study. A contiguity matrix effectively captures spatial relationships based on geographic adjacency, which is advantageous for analysing the dynamics of carbon emissions both within urban clusters and among neighbouring urban agglomerations. Furthermore, in the field of urban cluster carbon emission studies, the prevalent use of the contiguity matrix contributes to methodological consistency. This consistency facilitates comparative and synthetic analyses across different studies.

It is imperative to emphasize that SDM analysis yields two pivotal outcomes: direct and indirect effects. The direct effect delineates the influence of variations in specific indicators within a city on its own carbon emissions. The indirect effect characterizes the ramifications of changes in specific indicators in neighbouring cities on a city's carbon emissions; this effect is commonly termed the "spatial spillover effect". These effects are interrelated and collectively shape the dynamics of urban carbon emissions. This study further elucidates the impact mechanism of carbon emissions grounded in the computational outcomes of these two effects.

3.3.1.2. Spatial autocorrelation analysis. Spatial autocorrelation is a pivotal concept in spatial statistics that addresses the relationship between the attribute values of a geographic unit and its proximate counterparts. This concept predominantly delineates the spatial distribution pattern throughout a research area. Among the indicators for gauging spatial autocorrelation, Moran's I is particularly prevalent. When exploring the causal mechanisms of carbon emissions within urban conglomerates, spatial autocorrelation facilitates insights into the spatial dispersion of emissions and aids in pinpointing areas of spatial agglomeration. In this study, Moran's I was calculated to analyse the spatial distribution and clustering of carbon emissions in urban agglomerations. This analysis was conducted through a geographic information system (GIS) platform that facilitated the visualization and quantification of spatial relationships.

3.3.2. Indicator system construction and impact mechanism analysis

To address the primary objective of this study, the analysis of impact mechanisms, we constructed a comprehensive indicator system based on an extensive literature review. This system stratifies the determinants of carbon emissions into two broad categories—socioeconomic drivers and policy influences—and organizes them across three tiers—the system

Table 4
Indicator system for the carbon emissions of Chinese urban agglomerations.

System level	Guideline level	Indicator level
Socioeconomic drivers	Economic aggregate (Y. Wang, Yin et al., 2022; Wiedmann et al., 2020)	T-GDP (RMB_10000)
	Economic level (S. Wang et al., 2017; Wiedmann et al., 2020; Yin et al., 2023)	P-GDP (RMB_10000)
	Social consumption level (Dong & Li, 2022; Yin et al., 2023)	GRSCG (RMB 10000)
	Industrialization level (S. Wang et al., 2017; Yin et al., 2023)	SI-GDP (%)
	Service industry level (S. Wang et al., 2017; Yin et al., 2023)	ST-GDP (%)
	Population distribution (Liddle, 2015)	PD (p/km^2)
	Population size (Liddle, 2015; Y. Zhao et al., 2022)	PS (ten thousand)
	Urbanization rate (Dong & Li, 2022; Y. Zhao et al., 2022)	UBR (%)
Policy influences	Transport planning (S. Wang et al., 2017)	RA (10000 m^2)
	Public transport (Das et al., 2022; Muñoz et al., 2022)	NBO (Vehicle)
	Transport prosperity	RA-P (m^2)
	Urban land use	BA (km^2)
	Environmental planning (G. Liu & Zhang, 2022)	IEP-GDP (%)
	Environmental regulation (Cheng et al., 2022; Wiedmann et al., 2020)	REV-GWR (%)
	Number of green technologies (Y. Wang, Yin et al., 2022)	Green-TP
	Level of green technologies (C. Wang et al., 2014)	Green-TL (%)
	Capacity for government intervention (Kou & Xu, 2022)	FE-GDP (%)

level, guideline level, and indicator level—as shown in Table 4.

Socioeconomic development (including population changes, economic growth, and technological progress) inevitably increases energy consumption and emits CO_2, putting pressure on the environment (Y. Liu et al., 2015; Zhu & Peng, 2012, pp. 1978–2008). The impact of population factors and socioeconomic development processes on carbon emissions depends on factors such as household size (Fujimi et al., 2016) and the urbanization level (C. Zhang & Lin, 2012). In addition, economic growth often increases energy consumption and leads to more carbon emissions, and energy consumption is the main production factor influencing economic growth (Zhou et al., 2015). Energy consumption promotes economic growth, but it also inevitably emits carbon dioxide. Meanwhile, technological progress is closely related to energy intensity, and changes in production technology can reduce energy intensity (C. Wang et al., 2014; Zhou & Liu, 2016).

Governmental policies and management mechanisms play pivotal roles in influencing carbon emissions (Y. Wang, Yin et al., 2022). Considering the perspective of transportation planning and public transit systems, governmental policy decisions can directly impact urban transportation patterns and carbon emission levels. For instance, effective transportation planning and the provision of ample public transportation facilities are instrumental in this regard. Additionally, urban land-use policies, such as the control of the built-up area per square kilometre, can foster more efficient land use and energy consumption patterns, thus affecting carbon emissions. On the other hand, the formulation and implementation of environmental policies, such as investments in pollution control and the promotion of green technologies, can enhance energy efficiency and reduce carbon emissions (Chen et al., 2018). The proactive role of governments in promoting sustainable development, including the encouragement of innovation and the application of green technologies, is a key factor in achieving carbon emission reduction targets (Y. Wang, Yin et al., 2022).

In the analysis of socioeconomic drivers, a comprehensive suite of variables was examined, including economic aggregate (T-GDP), the economic level (P-GDP), the social consumption level (GRSCG), the industrialization level (SI-GDP), the service industry level (ST-GDP), the population distribution (PD), population size (PS), and the urbanization rate (UBP). These variables are fundamental for understanding the economic and social dimensions that influence carbon emissions. For instance, the economic aggregate and level have a direct impact on energy consumption and carbon emissions, while the urbanization rate and population distribution are instrumental in shaping energy use patterns and transportation structures. Collectively, these indicators encapsulate the economic and social contexts influencing urban carbon emissions.

In terms of policy influences, the assessment incorporated variables that are indicative of urban and environmental governance: transport planning (RA), public transport (NBO), transport prosperity (RA-P), urban land use(BA), environmental planning (IEP-GDP), environmental regulation (REV-GWR), in the number of green technologies (Green-TP), the level of green technologies (Green-TL), and the capacity for government intervention (FE-GDP). These indicators encompass various aspects of urban and environmental governance, such as the role of transportation infrastructure in carbon emission reduction and governmental efforts in fostering environmental protection and green technological innovation. Analysis of these policy-related indicators is pivotal in revealing the impact of policy decisions on the patterns of urban carbon emissions.

The analysis of the impact mechanism employed spatial econometric models to decompose the effects of these indicators into direct and indirect (spillover) effects on carbon emissions within and across cities. This methodological approach served to quantify the strength of the relationships between each indicator and carbon emissions and elucidated the interconnectedness of urban centres in terms of their environmental impact.

4. Results

4.1. Characteristics of the spatiotemporal evolution of carbon emissions

Although the carbon emissions of these three urban agglomerations have experienced fluctuations, the overall trend is an upwards trend, as illustrated in Fig. 3. Furthermore, the spatiotemporal distribution analysis of carbon emissions presented in Fig. 4 suggests a convergence towards higher emission values among the cities. For instance, in 2005, nine cities within these three urban agglomerations emitted more than 60 million tons of carbon. By 2020, this number had risen to 19 cities, constituting an increase of 111 %.

For the YRD urban agglomeration, between 2005 and 2010, the eastern Shanghai region dominated in terms of carbon emissions, with a spatial pattern gravitating mono-centrically towards Shanghai. Between 2015 and 2020, the core agglomeration area expanded outwards, evolving into a multicentric spatial configuration anchored by the primary Shanghai metropolitan area and complemented by secondary cores in Nanjing and Hangzhou. Specifically, the spatial pattern of carbon emissions typically aligns with a hierarchical "metropolitan area-urban agglomeration" dynamic, as carbon emissions are concentrated in megacities such as Shanghai, Nanjing, and Suzhou.

For the BTH urban agglomeration, from 2005 to 2020, the spatiotemporal evolutionary pattern displayed dual nuclei, with the eastern cities of Beijing and Tianjin and the southwestern region of the Shijiazhuang-Xingtai-Handan agglomeration. This spatial layout shows the metropolitan area-city cluster hierarchy of the BTH region.

For the PRD urban agglomeration, in 2005, carbon emissions displayed a pronounced inclination towards Guangzhou. By 2010, this trend radiated outwards from the "Guangzhou-Shenzhen-Foshan" nexus. From 2016 to 2020, the concentration of emissions manifested around megacities such as Guangzhou and Shenzhen, progressively spilling over to form a mega-single-centre agglomeration spatial pattern.

Moreover, an analysis of the spatial correlation of carbon emissions between cities within the YRD and PRD urban agglomerations reveals a notable link, in contrast to the BTH agglomeration, where such correlation is absent (Fig. 5). The Moran's I value, which indicates spatial dependence, shows an increasing trend for both the YRD and PRD regions, suggesting strengthened intracluster production interactions in recent years. This increasing trend means that a rise in carbon emissions in one city tends to lead to higher emissions in closely connected cities. However, the Moran's I results for the BTH urban agglomeration indicate a lack of significant interrelationships in emissions, indicating weaker synergy among its cities than between the YRD and PRD urban agglomerations.

4.2. Analysis of the driving forces of carbon emissions in Chinese urban agglomerations

Based on the Moran's I analysis, a significant correlation in carbon emissions was observed among cities within both the YRD and PRD regions (Figs. 6-9). This finding underscores the mutual influence of cities' carbon emissions, necessitating an in-depth exploration of the inherent causal mechanisms involved. Thus, the spatial econometric approach, complemented by the SDM, was deployed to dissect the carbon emission impact mechanisms within the YRD and PRD regions.

4.2.1. Direct effects—The internal driving factors of carbon emissions in urban agglomerations

4.2.1.1. Factors contributing to carbon emissions in urban agglomerations.

As shown in Figs. 6-9, *** indicates a significant correlation at the 0.01 level, ** indicates a significant correlation at the 0.05 level, and * indicates a significant correlation at the 0.1 level. Regarding socioeconomic drivers, from 2005 to 2009, the YRD urban agglomeration

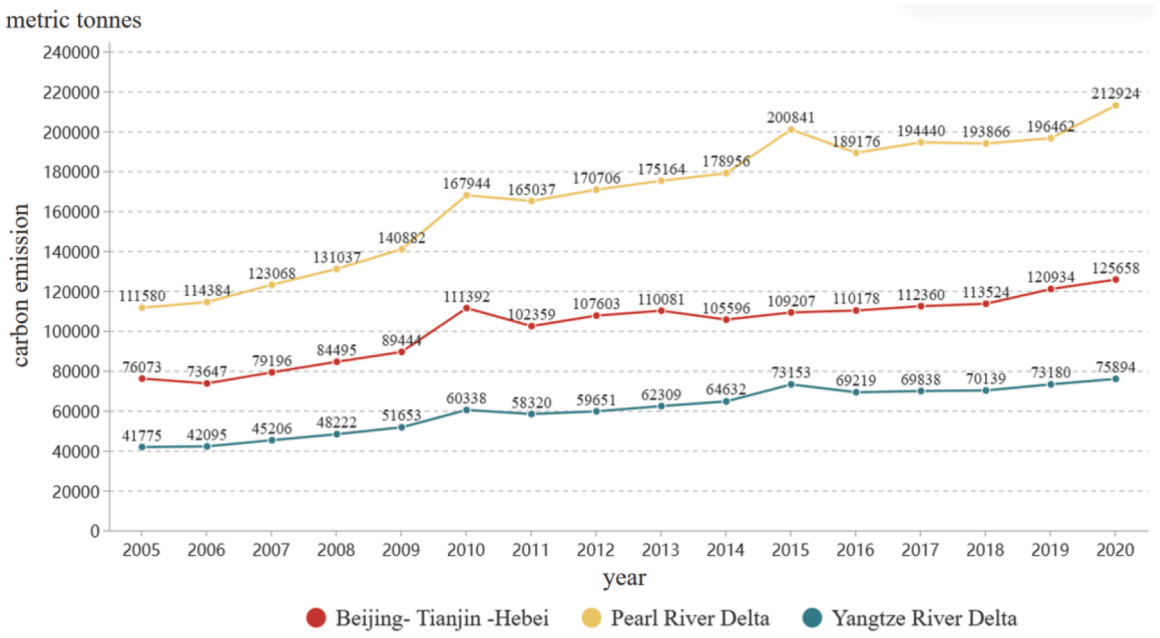


Fig. 3. Carbon emissions of three Chinese urban agglomerations, 2005–2020.

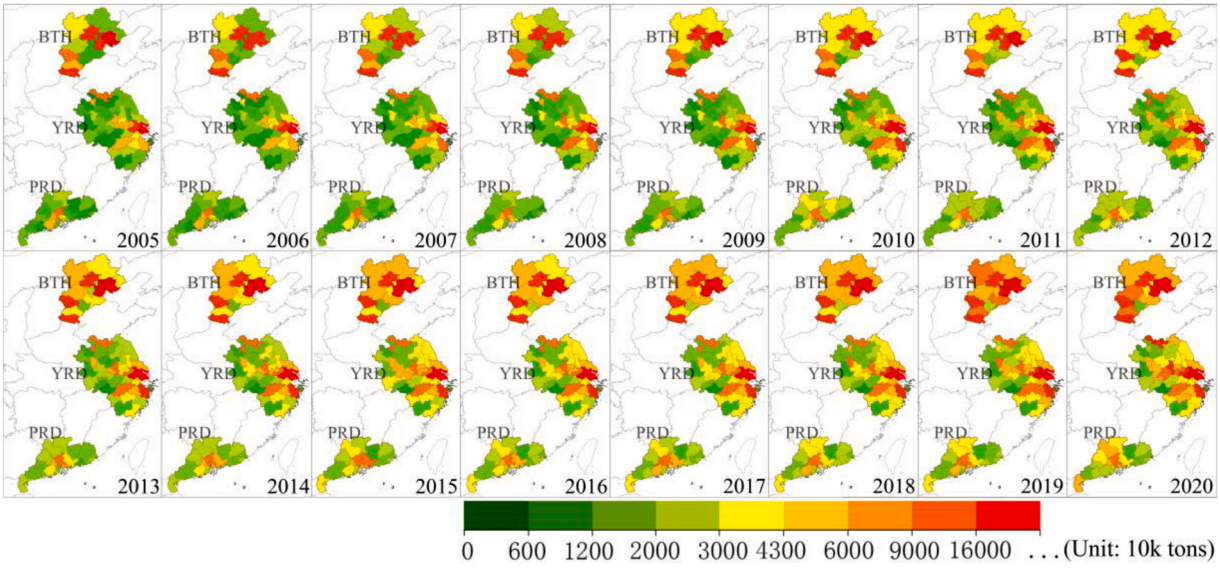


Fig. 4. Spatiotemporal distributions of carbon emissions in three Chinese urban agglomerations.

experienced an increase in carbon emissions driven by T-GDP (weight 1.221***) at the economic and social level (Fig. 6), while the PRD urban agglomeration was driven by P-GDP (weight 0.451***), SI-GDP (weight 0.528***), ST-GDP (weight 0.471***), and PS (weight 2.084***) (Fig. 8). Regarding policy influences, BA (weight 0.42***) and Green-TP (weight 0.129***) in the YRD region promoted carbon emissions (Fig. 7), while Green-TP (weight 0.459***) was the main driver in the PRD region (Fig. 9). These results indicate that although green technology has developed to some extent, it still cannot meet the rapidly growing energy demand of the two urban agglomerations as a whole. In particular, the YRD urban agglomeration expanded urban land use and increased energy consumption, while the PRD concentrated more on human resources, strengthened the secondary and tertiary industries, and experienced industrial restructuring, which led to greater energy consumption.

From 2010 to 2014, only the T-GDP (weight 0.873*) and UBR (weight 1.921***) of the PRD region were significantly positively correlated with carbon emissions (Fig. 8), while none of the factors in the YRD region were positively correlated with carbon emissions (Fig. 6). These results suggest that the PRD region is undergoing a rapid expansion stage and that the pace of urbanization is accelerating, which will increase carbon emissions. At the same time, the YRD region may be in an adaptation period of industrial upgrading and transformation.

From 2015 to 2020, the YRD region experienced an increase in carbon emissions due to its dependence on basic industries for high-quality development, as indicated by its SI-GDP (weight 0.126*) (Fig. 6). The PRD region experienced a shift towards a consumption-driven economic growth stage, as indicated by its GRSCG (weight 0.778*), following changes in urbanization, industrialization, and consumption structure (Fig. 8).

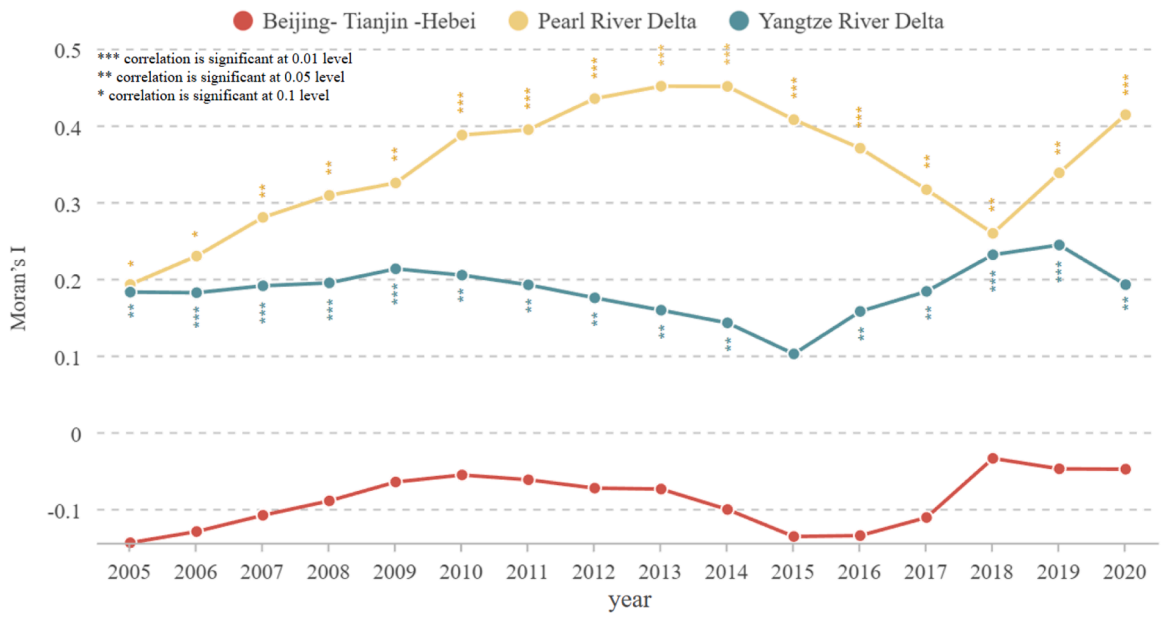


Fig. 5. Moran's I values across different urban agglomerations and years.

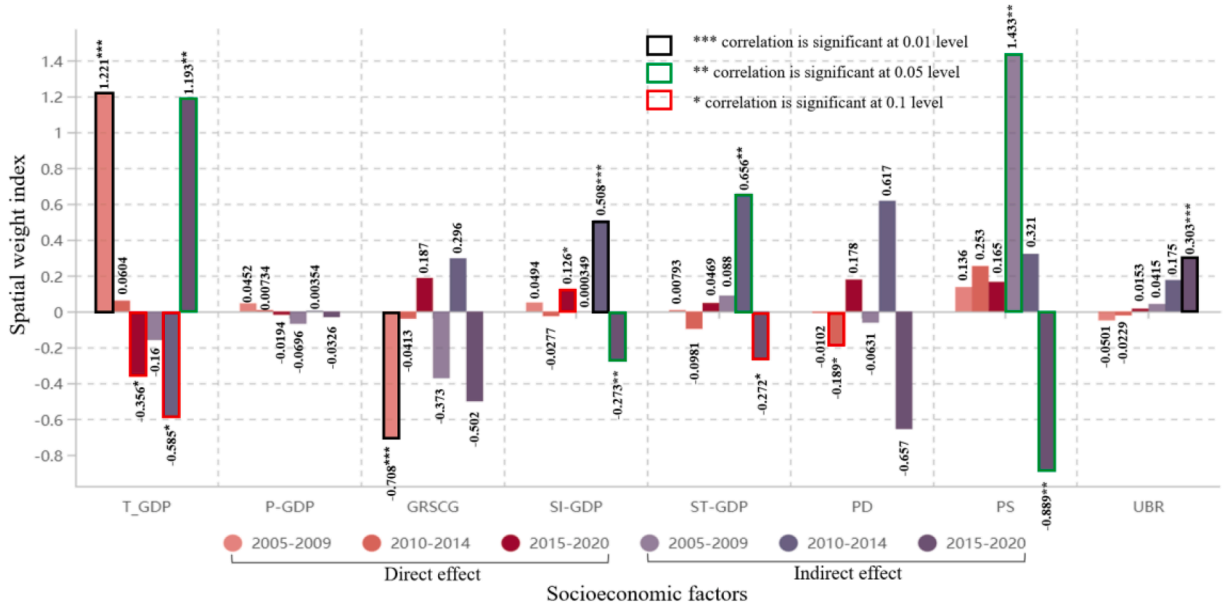


Fig. 6. The spatial weight index for socioeconomic factors impacting carbon emissions within the YRD urban agglomeration.

4.2.1.2. Factors influencing the suppression of carbon emissions in urban agglomerations. From 2005 to 2009, the carbon emissions in the YRD region were suppressed by GRSCG (weight −0.708***), REV-GWR (weight −0.0247**) and FE-GDP (weight −0.045*) (Fig. 6 and Fig. 7). The PRD region was affected by GRSCG (weight −1.04***) and NBO (weight −0.204 **) (Fig. 8). These negative effect coefficients indicate that the carbon emissions in the YRD were reduced due to policies, government governance, and public awareness. Although the weight is small, this reduction indicates that even subtle policy adjustments may have a positive impact on carbon emissions, which emphasizes the importance of detailed and sustained policy work. The PRD region reduced carbon emissions by promoting public transportation and optimizing the consumption structure and level. In terms of specific policy management, China first introduced targets for energy conservation and emission reduction in its Eleventh Five-Year Plan in 2006. Being among the most developed urban clusters in China, the YRD and PRD regions consequently took the lead in rolling out a series of policies and regulations related to energy savings and emission reduction. This series included raising emission standards for heavily polluting industries, promoting the use of cleaner energy sources, and implementing stricter energy efficiency standards in the construction and transportation sectors.

From 2010 to 2014, the YRD region reduced carbon emissions due to PD (weight −0.189*), REV-GWR (weight −0.0148*) and Green-TL (weight −0.0158**) (Fig. 7). These results indicate that the green technology and environmental regulations in the YRD region are gradually improving. Not only are green policies playing a certain role in reducing carbon emissions, but green technology is also gradually meeting the demand for energy-related carbon reduction, which indicates a gradual refinement in green technology and environmental regulation in the region. Notably, China's release of the "Automobile Industry Adjustment and Revitalization Plan" in 2009, which for the first

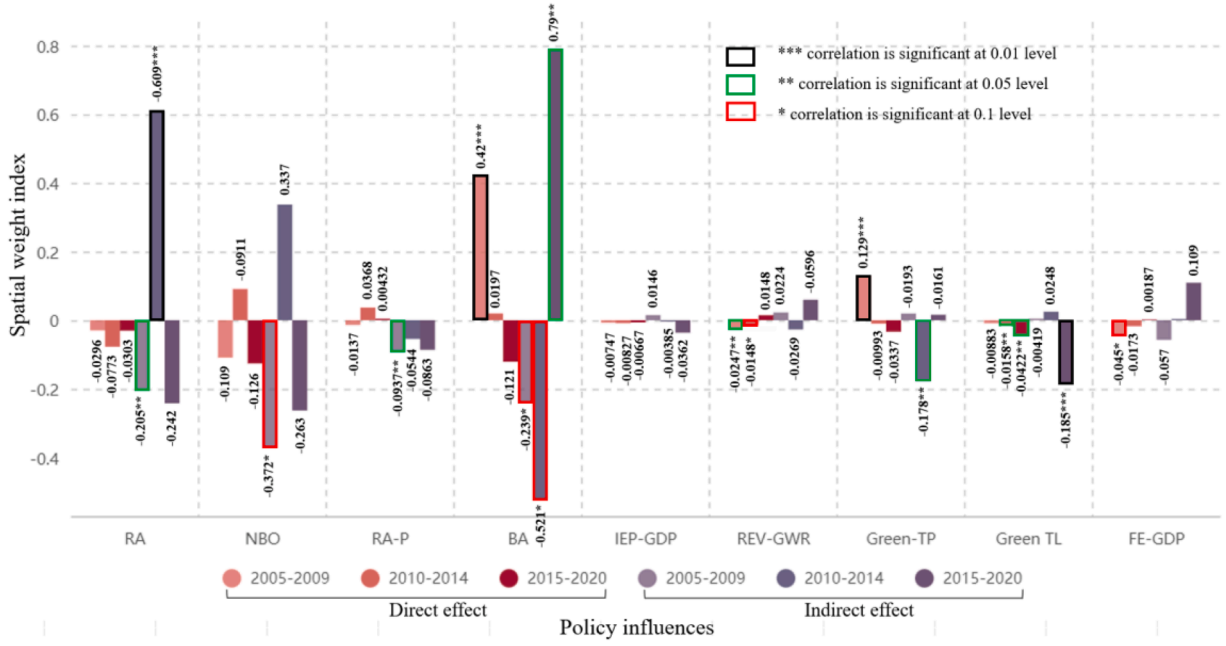


Fig. 7. The spatial weight index for policy factors impacting carbon emissions within the YRD urban agglomeration.

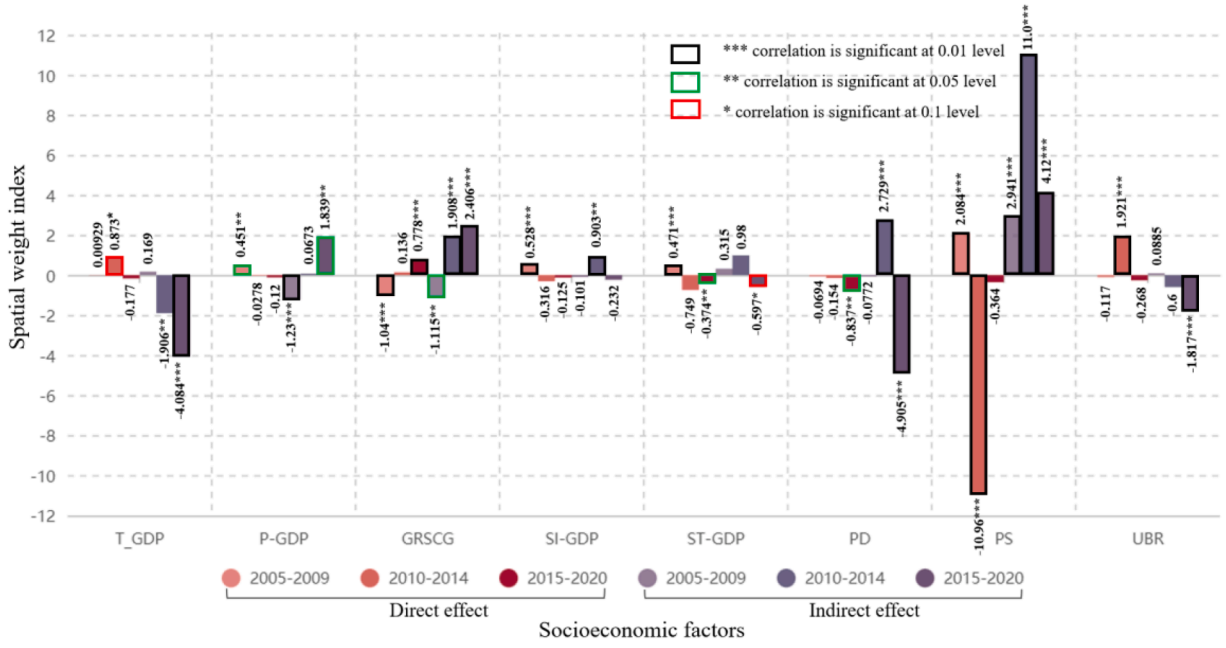


Fig. 8. The spatial weight index for socioeconomic factors impacting carbon emissions within the PRD urban agglomeration.

time mentioned fiscal subsidies for new energy, signified a new phase in energy-saving and emission-reduction development. This development suggests that not only do green policies play a significant role in carbon reduction but green technologies are also increasingly meeting the needs for energy conservation and emission reduction. However, in the PRD region, carbon emissions decreased due to PS (weight −10.96**) and FE-GDP (weight −0.441**) (Fig. 8 and Fig. 9), indicating that the government's efforts in environmental protection have gradually achieved the desired results. At the same time, population density can inhibit carbon emissions in both urban agglomerations, indicating that the government's policy measures for low-carbon lifestyles in areas with a high population density are beginning to take effect.

From 2015 to 2020, carbon emissions in the YRD region were negatively correlated with T-GDP (weight −0.356*) and Green-TL (weight −0.0422**) (Fig. 6 and Fig. 7). These results indicate that the region's economic growth and carbon emissions began to decouple and further confirm that it vigorously developed and promoted green technology during this period, which effectively controlled carbon emissions. For instance, in 2019, the YRD region issued the "Yangtze River Delta Ecological and Green Integration Development Demonstration Zone National Land Spatial Planning", signifying that the environmental governance of the urban cluster reached a new level of maturity. Additionally, substantial research and development (R&D) were invested in renewable energy technologies. On the other hand, the carbon emissions of the PRD urban agglomeration were suppressed by ST-GDP (weight −0.374**) and PD (weight −0.837***) (Fig. 8), indicating that

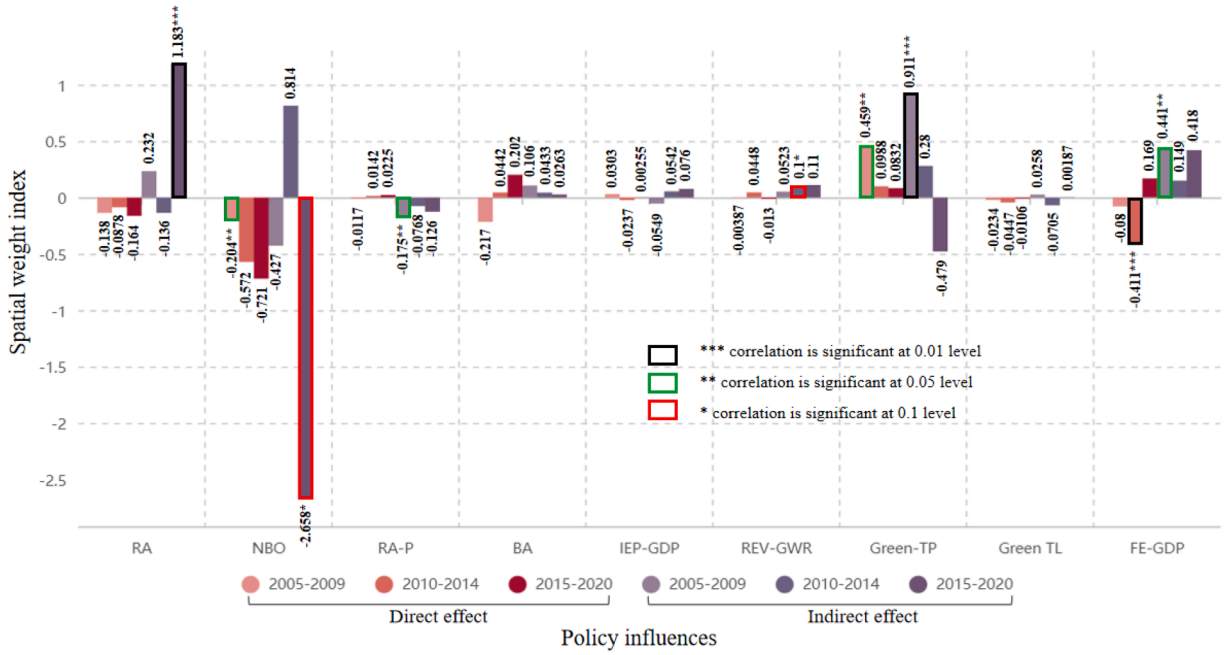


Fig. 9. The spatial weight index for policy factors impacting carbon emissions within the PRD urban agglomeration.

the development of the service industry in the PRD region was relatively rapid during this period. Compared with traditional manufacturing, the service industry often has lower carbon emissions. At the same time, the urbanization strategy in the PRD region has focused on a high-density, public transportation-based model. Moreover, the urbanization strategy of the PRD region has focused on high-density, public-transport-oriented models and strongly supported the development of the new energy vehicle industry. Although some areas have entered a stage of high-quality development, overall, the PRD region still lags behind the YRD region.

4.2.2. Indirect effects—Spatial spillover effect mechanism of carbon emissions in urban agglomerations

4.2.2.1. Factors contributing to carbon emissions in urban agglomerations. As shown in Figs. 6-9, *** indicates a significant correlation at the 0.01 level, ** indicates a significant correlation at the 0.05 level, and * indicates a significant correlation at the 0.1 level. From 2005 to 2009, for the socioeconomic drivers, the carbon emissions in cities of the YRD and PRD urban agglomerations were significantly positively correlated with the PS of adjacent cities, with weights of 1.433** and 2.941**, respectively (Fig. 6 and Fig. 8). For the policy influences, the carbon emissions of cities in the PRD region were significantly positively correlated with the Green-TP and FE-GDP of adjacent cities, with weights of 0.911*** and 0.441**, respectively (Fig. 9). These results show that the rapid development of cities during this period led to the accumulation of surrounding resources, thus reducing the carbon emissions of adjacent cities. However, the environmental protection policy is still at an early stage and is not flexible enough, leading to some high-carbon-emission activities moving from a city to neighbouring cities.

From 2010 to 2014, for the socioeconomic drivers, the carbon emissions in cities of the YRD region were significantly positively correlated with the SI-GDP and ST-GDP of adjacent cities, with weights of 0.508** and 0.656**, respectively (Fig. 6). The carbon emissions of cities in the PRD region were significantly positively correlated with the GRSCG, SI-GDP, PD and PS of adjacent cities, with weights of 1.908****, 0.903**, 2.729*** and 11**, respectively (Fig. 8). For the policy influences, the carbon emissions of cities in the YRD region were significantly positively correlated with the RA of adjacent cities, with a weight of 0.609*** (Fig. 7). The carbon emissions of cities in the PRD region were significantly positively correlated with the REV-GWR of adjacent cities, with a weight of 0.1*(Fig. 9). This result shows that for the YRD region, the siphon effect between cities is enhanced, and the interaction between industrial clusters and resource aggregation is significant, reflecting industrial complementarity. That is, with the development of the industrialization and service industry of a city, neighbouring cities may need to provide complementary products and services, leading to an increase in carbon emissions. However, the many population flows between cities in the PRD region mean that some cities experienced rapid urbanization during this period, leading to an increase in the development disparity of some cities in the PRD urban agglomeration; however, the interaction effect was not as significant as that of the YRD urban agglomeration. In addition, some high-carbon-emission activities were forced to migrate outside due to environmental regulations.

From 2015 to 2020, for the socioeconomic drivers, the carbon emissions in cities of the YRD region had a significant positive correlation with GDP and UBR, with weights of 1.193** and 0.303**, respectively (Fig. 6). The carbon emissions of cities in the PRD region were significantly positively correlated with the P-GDP, GRSCG and PS of adjacent cities, with weights of 1.839***, 2.406*** and 4.12***, respectively (Fig. 8). For the policy influences, the carbon emissions of cities in the YRD region were significantly positively correlated with the BA of adjacent cities, with a weight of 0.79** (Fig. 7). The carbon emissions of cities in the PRD were significantly positively correlated with the RA of adjacent cities, with a weight of 1.183*** (Fig. 9). This result shows that during this period, the YRD urban agglomeration faced volatile growth, some regions still needed further development, and the trend of high-carbon industry transfer to these regions was obvious. The regional synergy of the PRD urban agglomeration was strengthening, as was the interaction between cities.

4.2.2.2. Factors influencing the suppression of carbon emissions in urban agglomerations. From 2005 to 2009, for the socioeconomic drivers, the carbon emissions in cities of the PRD were significantly negatively correlated with the P-GDP (weight −1.23***) and GRSCG (weight −1.115**) of the socioeconomic drivers of adjacent cities (Fig. 8). For the policy influences, carbon emissions in cities of the PRD region were significantly negatively correlated with RA-P (weight −0.175**)

(Fig. 9), while carbon emissions in the YRD region were significantly negatively correlated with RA (weight −0.205**), NBO (weight −0.372*), RA-P (weight −0.0937**), and BA (weight −0.239*) (Fig. 7). These results show that although the rapid development of some cities has successfully attracted more resources, thereby reducing the carbon emissions of surrounding cities, the development level of each city was similar, indicating that the "siphon effect" of urban development was not significant and that the policies of the YRD region at that time were more inclined to encourage public transport and reasonable urban planning to reduce carbon emissions.

From 2010 to 2014, the carbon emissions in the YRD region exhibited significant negative correlations with T-GDP (weight −0.585*), BA (weight −0.521*), and Green-TP (weight −0.178**) from the policy influence layer (Fig. 6 and Fig. 7). These results suggest an intensifying "siphon effect" in several cities within the YRD region during this period. Economic and technological advancements in these urban conglomerates led to a pronounced aggregation of resources and enhanced industrial cluster cooperation between cities, marked by notable interaction effects of various factors. Additionally, the diffusion of green technology had manifested. Meanwhile, the carbon emissions in the PRD region had a significant negative correlation with T-GDP (weight −1.906**) (Fig. 8). This result reveals a strengthening "siphon effect" in specific cities within the agglomeration, drawing resources and industries from neighbouring cities and consequently reducing their carbon emissions. Furthermore, the developmental disparity between these advanced regional cities and other regions surpassed that in the YRD region, and the interactive effects were not as pronounced as those observed in the YRD region.

From 2015 to 2020, the carbon emissions in cities of the YRD showed a pronounced negative correlation with SI-GDP (weight −0.273**), PS (weight −0.889*), and Green-TL (weight −0.185***) associated with adjacent cities' economic and social parameters (Fig. 6 and Fig. 7). These results suggest that the growth of the YRD urban agglomeration during this time frame was characterized by volatility. While a decoupling effect between overall economic advancement and carbon emissions was observed, certain cities continued to exhibit high energy consumption. For cities within the PRD region, carbon emissions had significant negative correlations with T-GDP (weight −4.084***), ST-GDP (weight −0.597*), PD (weight −4.905***), UBR (weight −1.817**), and NBO (weight −2.658*) from the policy influence layer (Fig. 8 and Fig. 9). These results imply a mounting attraction of the core cities within the urban agglomeration, possibly leading to a heightened concentration of population and resources in these central cities, while neighbouring cities displayed relative stagnation.

5. Discussion

5.1. The carbon emission characteristics vary across different development stages

Based on the analysis above, the stages and levels of development of China's BTH, PRD, and YRD urban agglomerations can be divided into early, growth, and maturity stages. First, the BTH urban agglomeration (early stage), which has a clear boundary between cities and rural areas, has emissions that are significantly uncorrelated between cities, poor intercity synergies, and a likely upwards trend in carbon emissions due to increased industrial production and infrastructure development. Energy efficiency is low, the dependence on fossil fuels is high, and carbon emissions are much greater than those in the other urban agglomerations. In urban agglomerations, the imbalance in development has led to a "siphon effect" of the BTH region, the surrounding areas are more undeveloped, and the key challenge is solving synergistic and pollution control problems.

Second, the PRD urban agglomeration (growth stage) has rapid economic growth, obvious industrial transformation, and narrowing urban–rural differences. Analyses show that with rapid economic growth and increased consumption, carbon emissions may sharply increase. Despite improvements in technology and energy efficiency, absolute carbon emissions will still increase due to increased production, and the spatial characteristics of carbon emissions between cities are more concentrated, matching areas with high economic activity and population density. The government's ability to intervene in carbon emissions is increasing, showing a significant correlation with carbon emissions. However, it is still in the stage of consuming a large amount of fossil fuels to develop the economy and society. The key issue is to accelerate industrial upgrading and enhance the essential flow of resources, such as talent.

Finally, there is the YRD urban agglomeration (maturity stage), marked by steady economic growth; this cluster has realized its industrial transformation and is dominated by the service sector. The integration between urban and rural zones is pronounced, and the ethos of green and sustainable development has become ingrained within the populace. The analysis establishes the YRD as the most advanced among the three major urban agglomerations, as it boasts balanced regional development and heightened interregional synergy. As inferred from Section 4, the GDP growth of this cluster over the 2015–2020 period reflects industrial rejuvenation. The correlation between carbon emissions and economic growth is evolving, signalling a decoupling effect where economic expansion no longer guarantees a corresponding increase in carbon emissions. Factors such as technological innovations, energy mix optimization, and stringent policies may facilitate a relative decline in carbon emissions. Within the agglomeration, carbon emissions might exhibit polycentricity. The primary challenge focuses on fostering fluid and organized factor flows between regions to achieve integrated and high-quality development.

5.2. The decoupling effect between carbon emissions and economic development

From 2015 to 2020, the YRD urban agglomeration demonstrated a notable negative correlation between GDP growth and carbon emissions. To elucidate this trend, a comprehensive quantitative analysis was performed, assessing the GDP, carbon dioxide growth rate, and economic growth rate of the YRD from 2005 to 2020 (Fig. 10). This analysis revealed that between 2005 and 2014, the carbon emission rate mirrored the economic growth rate; as one increased or decreased, so did the other. However, after 2014, these metrics diverged, with the regional GDP consistently rising, independent of carbon emissions. These findings corroborate the observed decoupling of carbon emissions from economic growth in the YRD urban agglomeration from 2015 to 2020. For the purposes of this study, the decoupling effect describes a timeframe in which the rate of economic growth surpasses that of energy consumption, manifesting as a diminishing association between economic growth and GHG emissions until eventual divergence.

During the nascent phases of swift urbanization and industrialization, urban agglomerations typically rely heavily on energy-intensive practices, propelling carbon emissions (Y. He et al., 2021). However, as these agglomerations transition into their intermediate stages, diverse factors such as economic maturation, shifts in industrial configurations, and technological advancements encourage a pivot towards cleaner energy sources. This transition marks a distinct alteration in the nexus between carbon emissions and economic growth, eroding their previously observed synchrony (R. Li et al., 2022; Yao et al., 2021). As these agglomerations mature, the decoupling between carbon emissions and economic growth becomes more pronounced. This relationship attenuates to the extent that even amidst persistent economic expansion, the pace of carbon emissions decelerates (Q. Wang et al., 2018). Furthermore, as urban agglomerations continue evolving socioeconomically, facilitated by industrial evolution, energy restructuring, and technological innovations, the decoupling effect intensifies (Soytas & Sari, 2009; Y. Yu et al., 2023). Consequently, even as economies flourish, carbon emissions stabilize or recede. This dynamic is encapsulated in the

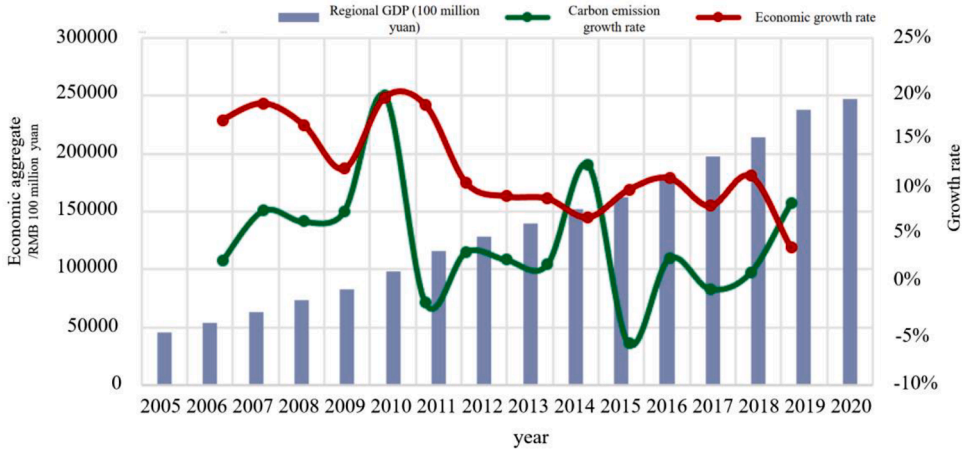


Fig. 10. Relationship between economic growth and carbon emissions in the YRD urban agglomeration.

decoupling effect curve presented in Fig. 11.

5.3. *Key driving factors and policy implications for the carbon emissions of urban agglomerations in different periods*

In the initial stages of urban agglomeration, heightened industrial activities combined with low energy efficiency result in substantial energy consumption (Cai & Hu, 2022; Y. Li et al., 2018). Factors such as economic growth, enhanced industrialization, population concentration, and urban land expansion contribute to this significant energy intake. Core cities within urban agglomerations tend to exert a "resource-draining" effect on peripheral areas. This effect, coupled with insufficient ecological attention, propels the growth of core cities but leaves surrounding areas lagging. While advancements in public transportation, enhanced government oversight, and stricter environmental regulations can contribute to reducing carbon emissions, it is important to recognize that these measures might not uniformly apply to all urban areas. Hence, tailored approaches are needed for different urban zones to address their unique challenges and opportunities in carbon emission reduction.

During the urban agglomeration growth phase, the aggregation of resources bolsters technological advancement and energy use efficiency (Y. Wang, Yin et al., 2022), potentially enhancing public transportation usage and thus lowering carbon emissions. Nevertheless, as these urban conglomerations swell in population, the ensuing strain exacerbates energy consumption and traffic congestion, which in turn elevates carbon emissions (W. Li et al., 2023; X. Zhang & Zhang, 2023). In the formative stages of global urban agglomerations, it is crucial to heed these dynamics and circumvent resource wastage from abrupt, large-scale population clustering. Concurrently, while burgeoning metropolitan areas within these agglomerations might experience elevated carbon emissions, urban sprawl and land-use optimization could reverse this trend. These metropolitan hubs, typified by a dense population and resource concentration, usually serve as administrative, economic, cultural, and political epicentres on both the regional and national scales (Snow et al., 2004). Their carbon footprints are consequently amplified, revealing a pronounced central agglomeration trait. This centralization fosters the trend where metropolitan areas first flourish, with peripheral regions trailing (Pastor, 2000). The carbon reduction imperative during this stage hinges on expediting industrial evolution, endorsing shifts from heavy to light and service industries, drafting apt energy policies, championing renewable energy, reducing fossil fuel reliance, optimizing resource mobility, and bridging the urban–rural divide.

In the maturity phase of urban agglomeration, economic expansion becomes more stable, most industrial transformations are finalized, and cities become intricately interwoven. Analyses of the 2015–2020 period indicate that green technology substantially curtails the carbon emissions of the YRD urban agglomeration. However, there are observed inconsequential correlations between governmental oversight, environmental regulations, and the carbon footprints of cities in the YRD and PRD regions. Intriguingly, economic growth in urban agglomerations and carbon emission growth exhibit a negative correlation, suggesting that technological strides and resource flow conveniences profoundly

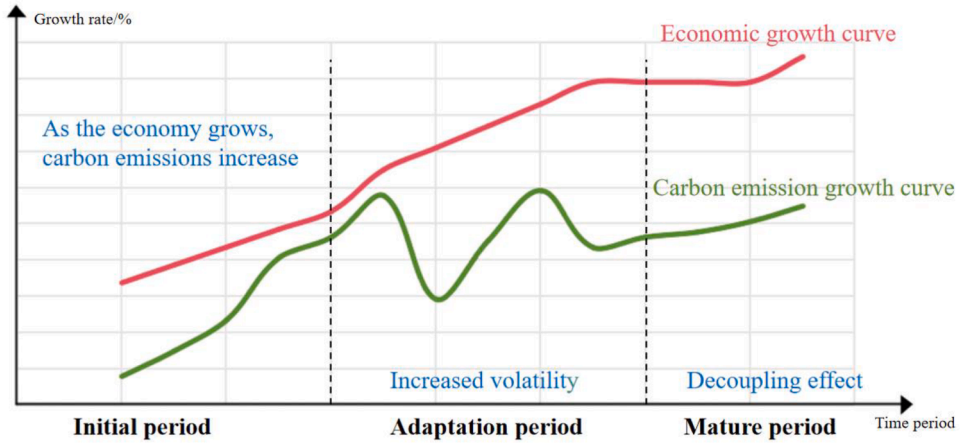


Fig. 11. Decoupling effect between carbon emissions and economic development.

impact city carbon outputs at this juncture. It is evident that governmental interventions and environmental regulations are not correlated with urban carbon emissions, particularly during advanced urban agglomeration phases. Thus, the crux of carbon reduction at this juncture is rooted in technological advancement, market liberalization, augmented resource flow, and incentivizing green technological R&D. These strategies can elevate the integrative development quality of urban agglomerations, optimize resource use, and consequently reduce carbon emissions.

5.4. Policy implications for carbon governance in China

1) **Phased Emission Reduction Strategies:** Given the differing characteristics and challenges of carbon emissions at various stages of urban cluster development, policymakers should formulate stage-specific reduction strategies. For urban clusters in the initial stage, policies should focus on improving energy efficiency and controlling industrial emissions. In the growth stage, the emphasis should be on promoting the optimization of industrial structures and the transformation of energy systems. For mature urban clusters, it is essential to foster green technological innovation and to decouple economic growth from carbon emissions.
2) **Comprehensive Policy Framework:** Policies should encompass economic, social, and environmental factors to form a holistic policy framework. This includes developing incentive measures to encourage the use of clean energy, fostering technological innovation, and promoting public transportation and green urban planning.
3) **Region-Specific Policy Design:** Considering the unique characteristics and needs of different urban clusters, policies should be tailored to ensure their effectiveness. For example, in resource-based cities, the focus might be on transformation and upgrading as well as the development of alternative industries. Conversely, in high-tech cities, further advancing technological innovation and the construction of smart cities could be prioritized.

5.5. Limitations and possible future research directions

This study has certain limitations. First, due to the availability and completeness of publicly available data, we selected only prefecture-level cities from three typical urban agglomerations in China as a case study, resulting in an insufficient sample size and limited research breadth. Second, this study did not consider the individual effects of existing data, which may result in insufficient depth and accuracy in interpreting the specific meanings behind the data for certain specific cities or regions. Finally, the carbon emissions of this study were the overall carbon emissions, without considering the specific impact of carbon emissions from different production and living sectors in detail.

Future research directions may include comprehensive studies across urban clusters, comparing the similarities and differences in carbon emission patterns among various urban agglomerations, as well as investigations of the effectiveness of different policies in diverse urban settings. Such comparative analyses are crucial for formulating more effective regional and national policies. The establishment of long-term carbon emission monitoring and prediction models is also of paramount importance as a tool for assessing future development trends and the impact of policies. Furthermore, research combining technological innovation with policy, such as the integration of carbon capture and storage, renewable energy technologies with tax incentives, subsidies, and carbon trading, represents a significant direction for future studies. In addition, exploring the role of social behaviour and cultural factors, regional collaboration, and integrated development strategies, as well as studies on adaptive and resilient urban planning, will provide essential theoretical support and practical guidance for the carbon reduction and sustainable development of urban clusters.

6. Conclusion

First, this study reveals that although urban agglomerations are experiencing a year-on-year increase in carbon emissions, the disparity in emissions between cities is gradually narrowing. The spatiotemporal pattern of carbon emissions essentially reflects the hierarchical "metropolitan circle-urban agglomeration" relationship. Notably, the YRD and PRD urban agglomerations show a significant positive spatial correlation in carbon emissions, characterized by strong central aggregation. In contrast, the BTH urban agglomeration demonstrates no such spatial correlation, with carbon emissions in cities other than Beijing increasing, revealing a trend of high-carbon-emission regional clustering without a strong central feature.

Second, this study highlights that the temporal and spatial evolution of carbon emissions in urban agglomerations exhibits a significant spatial spillover effect. This finding indicates that when neighbouring cities have high levels of carbon emissions, the likelihood of elevated emissions in a city increases, and vice versa. Particularly in the YRD and PRD regions, the impacts of various elements at the socioeconomic and policy levels on the carbon emissions of urban agglomerations differ at different time points, reflecting a complex interplay of influences.

Third, based on the different developmental stages of urban agglomerations, this study proposes corresponding carbon reduction suggestions. For the YRD and PRD regions, it was found that from 2005 to 2009, the carbon emissions in the YRD region were primarily driven by economic growth (T_GDP), while those in the PRD region were influenced by multiple economic and social factors (such as P-GDP, SI-GDP, and ST-GDP). From 2010 to 2014, the PRD's T_GDP and urbanization rate (UBR) were significantly positively correlated with carbon emissions, whereas the YRD showed signs of industrial upgrading and transformation. From 2015 to 2020, the dependence on basic industries (SI-GDP) in the YRD region led to an increase in carbon emissions, while the PRD region entered a consumer-driven economic growth phase due to changes in its consumption structure (GRSCG). Therefore, carbon reduction strategies for urban agglomerations should be tailored based on their development stage and specific driving factors. For instance, the YRD region should focus on promoting green technology, while the PRD region should concentrate on adjusting its industrial structure and consumption patterns. These strategies are crucial for achieving sustainable development and reducing carbon emissions.

Finally, this study also revealed a decoupling phenomenon between the level of carbon emissions and economic growth in urban agglomerations. As economic and social development matures, the renewal of industries and technologies leads to a decoupling effect between carbon emissions and economic growth. Additionally, the agglomeration effect of population and scale leads to resource concentration, resulting in an initial increase in carbon emissions, followed by a reduction in later stages. Particularly in cities with high concentrations of population and material resources, such as capital cities or regional or even national political, economic, and cultural centres, carbon emissions are highly concentrated, exhibiting strong central aggregation features and radiating outwards with further urban development. The conclusions of this study hold significant reference value for the low-carbon development of urban agglomerations in China and globally. The planning and development of urban agglomerations should aim to optimize industrial structures, enhance the level of green technological advancement, streamline government management processes, and improve the efficiency of resource element flow within a region, thereby enhancing the energy savings and emission reduction goals of urban agglomerations. These measures not only help combat climate change but also promote a sustainable model of urban development and lifestyle transformation. The successful low-carbon transformation of urban agglomerations, which are pivotal engines for national and regional development, offers valuable experience and insights for global carbon reduction efforts.

CRediT authorship contribution statement

Meng Wei: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing, Project administration, Resources, Software. **Zhi Cai:** Conceptualization, Supervision, Validation, Writing – review & editing, Formal analysis, Project administration, Visualization. **Yan Song:** Funding acquisition, Project administration, Supervision, Writing – review & editing. **Jiangang Xu:** Data curation, Funding acquisition, Supervision. **Muqiu Lu:** Data curation, Project administration.

Declaration of competing interest

The authors declared that they have no conflicts of interest to this work.

Data availability

The authors do not have permission to share data.

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