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Proposing carbon reduction strategies for mega-urban agglomerations – a cluster analysis based on carbon emission intensity

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ABSTRACT

Identifying the causes of heterogeneity in carbon emission (CE) performance among different units of a mega-urban agglomeration is crucial for its low-carbon development. This study examines the impacts of regional industrial transformation, living consumption, and spatial expansion on CE using an extended Kaya identity model, focusing on 26 Yangtze River Delta (YRD) cities from 2006 to 2019. Our study reveals that: (1) The development disparities across YRD cities result in distinct CE reduction trajectories, with advanced urban centers showcasing more effective emission control strategies. (2) Living consumption is the primary driver of CE increases, contributing significantly to the rise with a proportion of 137.2%. This is moderated by industrial transformation, which has implemented efficiency improvements and technological innovations to reduce emissions, contributing to a decrease in CE by 48.9%. Spatial expansion also plays a role, accounting for an 11.7% increase in CE. (3) The YRD's CE reduction efforts are primarily concentrated in core cities, manifesting a pronounced core-periphery structure that includes spillover effects into transitional and peripheral cities. We propose targeted strategies, including incentivizing green technology in high-emission sectors, developing comprehensive low-carbon public transportation, and encouraging sustainable consumer behaviors through education and incentives. These strategies aim for a balanced advancement in industrial practices, urban planning, and public engagement, providing a roadmap for crafting sustainable urban development strategies in similar global contexts.

1. Introduction

Urban agglomerations, though occupying a mere fraction of the global land area—less than 4 %—are major contributors to global carbon emissions (CE), responsible for over 70 % of the worldwide total (Seto et al., 2012). With the escalating global urbanization trend, the proportion of urban carbon emissions in the global carbon emission process is anticipated to rise further (Zhu et al., 2022). Globally, cities serve as significant contributors to carbon emissions due to their concentrated population, industries, and transportation systems, making them both key sources and sinks in the carbon emission process.

In the face of accelerating urbanization, the critical role of mega-urban agglomerations—comprising both core and peripheral cities—in driving carbon emissions (CE) is increasingly evident. Research illustrates that industries reliant on fossil fuels and technology-intensive sectors are key drivers of CE growth(Jia et al., 2018; Jia et al., 2023). This is compounded by market consumption behaviors shaped by economic development and migration from rural to urban settings, which not only escalate CE but can also mitigate it when consumer preferences shift towards green products(Lim et al., 2022; Zhu et al., 2023). Additionally, spatial expansion affects CE through land-use changes and increased motorized transportation, further complicated by the 'core-periphery' model wherein core cities host advanced, high-CE industries, while peripheral regions become pollution havens (Guo et al., 2023; Ma and Shi, 2023; Song and Feng, 2023). This multifaceted landscape, characterized by 'neighbor avoidance effects' and regional disparities, necessitates a nuanced approach to CE reduction(Youngsteadt et al., 2023). Our study aims to dissect these intertwined factors in urban

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agglomerations, illuminating pathways to tailored CE reduction strategies.

In light of this, several research gaps become evident. Firstly, most existing studies focus on unidimensional influencing factors of carbon emissions, neglecting the complexity of urban agglomerations(Diaz, 2022; Jahanger et al., 2022). Secondly, there's a scarcity of work that considers both population and land urbanization effects on carbon emissions in mega-city development. Lastly, previous studies focus on individual cities, lacking an in-depth analysis of spatial heterogeneity within and between cities in an urban agglomeration (Table S1).

This paper addresses critical research gaps in understanding CE in urban agglomerations. It focuses on quantifying the diverse factors contributing to CE, such as consumption patterns, industrial transformation, and spatial expansion (Fig. 1). The study explores the variation in CE drivers across different urban areas and proposes tailored reduction strategies based on the unique characteristics and CE profiles of these areas. The aim is to offer a comprehensive analysis of CE dynamics, facilitating the development of effective, localized strategies for sustainable urban development.

The marginal contribution of this paper is mainly the following three points. (1) This study transcends traditional unidimensional approaches by offering a comprehensive examination of the multifaceted factors influencing carbon emissions in urban agglomerations. (2) The research integrates the impacts of both population growth and land urbanization, providing an enriched analysis of carbon emissions in the context of mega-city development. (3) By analyzing variations both between and within cities, this paper delves into the spatial heterogeneity within urban agglomerations and contributes to more nuanced, location-specific carbon emission reduction strategies.

2. Literature review

The identification and analysis of the driving factors behind carbon emissions in urban agglomerations have been a focal point of numerous studies, yet there is no uniform agreement on a comprehensive methodological approach(Robaina-Alves et al., 2016). Several methodological approaches have gained prominence for elucidating the driving factors behind emissions(Lin et al., 2023). One of the most frequently employed frameworks is the Kaya Identity, which decomposes emissions into contributing elements such as population, GDP per capita, and energy intensity(Ortega-Ruiz et al., 2020). Additionally, the LMDI has been widely adopted for its capability to isolate individual effects of multiple influencing factors(Jia et al., 2019). This method is particularly useful in assessing sectoral contributions to overall emissions and has been adapted for both temporal and spatial analyses(Jia et al., 2021). Structural Decomposition Analysis (SDA), another pivotal methodology, employs input–output tables to dissect the influences of economic structure and technological change on emissions (Su and Ang, 2012). These methods collectively offer robust and versatile tools for understanding the multifaceted drivers of CE, but are criticized for their simplistic structure (Wang et al., 2022).

Recent studies have taken a more multidimensional approach, incorporating economic, technological, and social factors. For instance, Li et al. (2022) applied multi-scale geographic weighted analysis method to analyze the impact of socio-economic factors and urban morphology on CE in cities at different stages of development. Such studies advance the discourse by providing a nuanced understanding of the regional structural differences that contribute to varying emission levels. Another methodological trend involves the use of geospatial analysis to study the 'core-periphery' model(Tang et al., 2021), helping to identify pollution havens and CE spillovers within and between cities.

Understanding the driving factors of CE in urban agglomerations sets the stage for devising effective mitigation strategies. As we transition from identifying and analyzing these factors—ranging from economic and technological influences to social behaviors—the focus shifts towards applying this knowledge. This progression underscores the importance of integrating insights on CE drivers with targeted actions for CE reduction.

Mitigating carbon emissions in sprawling urban agglomerations is a complex and multi-faceted challenge that has captured significant scholarly attention(Jiang and Ashworth, 2021). The research can be categorized along several lines, including technological advancements,

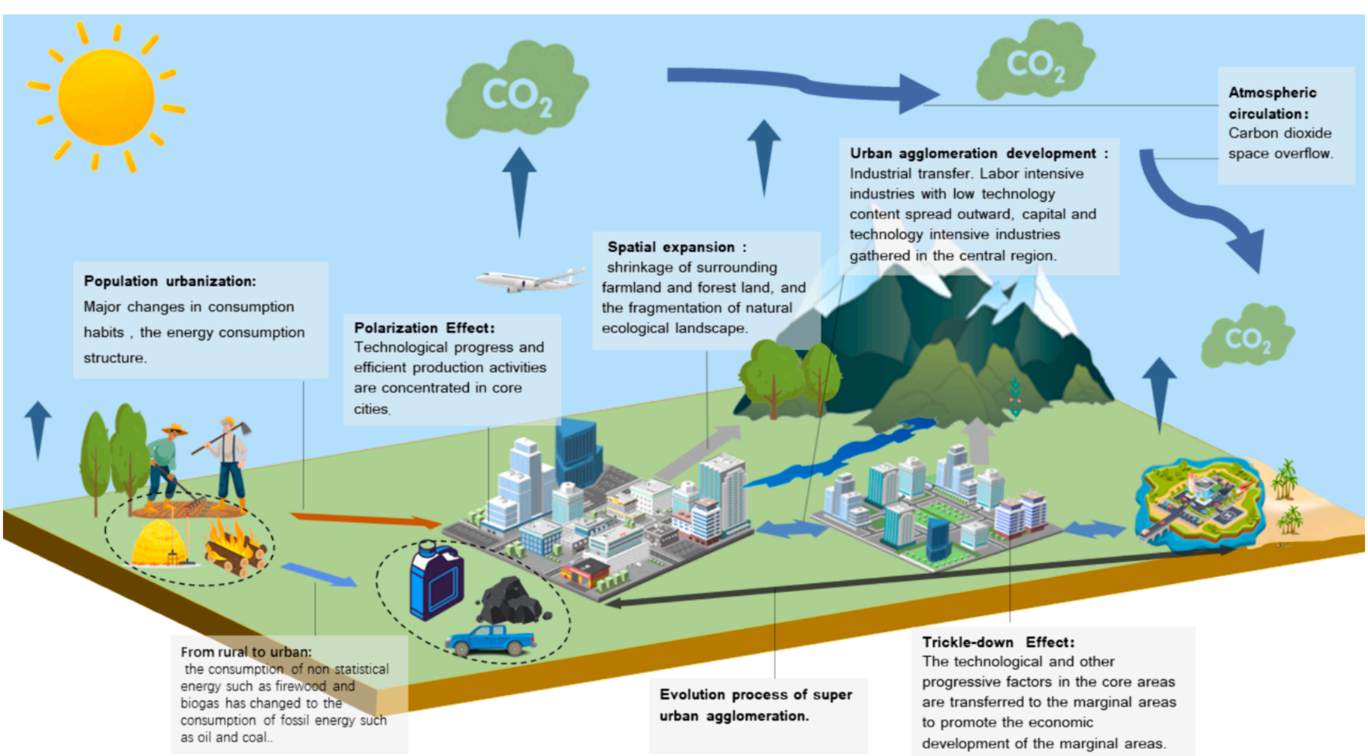

Fig. 1. Multiple sources of cluster CE in urban agglomeration development.

policy interventions, and public behavior modifications(Rissman et al., 2020; Sarkodie et al., 2020). One of the most direct methods to control carbon emissions is through the adoption of cleaner technologies. Zhang et al. (2020) explored how innovations in manufacturing processes can substantially reduce the carbon footprint of industries. Apart from manufacturing, cleaner energy sources like wind and solar have been cited as crucial in curbing emissions (Pata, 2021). Smart grids and energy-efficient building designs also come under this category, offering more sustainable energy utilization in residential and commercial structures(Lamnatou et al., 2022).

Policy tools are crucial in influencing both corporate and public behavior. Emission trading schemes, for instance, provide economic incentives for companies to reduce their carbon output (Chu et al., 2021). Other policy measures include urban planning initiatives designed to reduce the need for private car usage, thereby decreasing emissions from transportation (Browne et al., 2012). While these approaches have shown promise, there is a consensus that policy measures must be tailored to the specificities of each urban agglomeration, considering their unique industrial make-up and consumption patterns (Chen et al., 2017; Gao and Yuan, 2022).

Through literature review, we found two major research gaps:

(1) There exists a notable research gap in examining the combined impact of population growth and land urbanization on carbon emissions in mega-cities. Additionally, there is a scarcity of studies offering an integrated framework to fully capture the complexity of these driving factors. Most research has been city-specific, with limited exploration of the interactions between core and peripheral areas (Yin et al., 2023).

(2) Methodologically, current studies predominantly focus on isolated factors like population growth or industrial activity, neglecting the cumulative effects of urbanization on carbon emissions in mega-city development. The spatial heterogeneity of carbon emissions, both within and between cities in urban agglomerations, has yet to be comprehensively explored.

3. Method and materials

This study adopts a comprehensive research framework to investigate the heterogeneity of CE patterns in mega-urban agglomerations, with a specific focus on the YRD. Methodologically, the research integrates an extended Kaya identity model, which serves to quantify the impacts of regional industrial transformation, consumption shifts, and spatial expansion on CE. Industrial transformation includes technological progress effect (TE), structural adjustment effect (SE) and consumption inhibition effect (CRE), living consumption includes per capita living effect (LPE), resident consumption effect (HCE) and population size effect (PE), and spatial expansion includes production urbanization effect (UE), urbanization effect (PSE), population density effect (HDE) and spatial expansion effect (AE). The study aims to identify the critical factors contributing to carbon emissions and propose targeted reduction strategies. The research framework of this paper is shown in Fig. 2.

3.1. Study area

As the region with the highest degree of economic development in China and one of the six mega-urban agglomerations in the world, the Yangtze River Delta (YRD) region shoulders the strategic mission of exploring the new regional development pattern (Fig. 3). It is also an important region for achieving the goal of "carbon peaking and carbon neutrality". At present, the YRD mega-urban agglomeration faces three major problems. First, the superposition of the population peak and carbon peak will exert great pressure on the sustainable development of urban agglomerations(Chen et al., 2023). Second, the high-speed urbanization process leads to continuous growth in CE(Shen et al., 2021). Third, industrial structure transformation and upgrading have entered a bottleneck period(Liang et al., 2022). These issues are not conducive to the sustainable development of the YRD mega-urban agglomeration, and effective control of CE has currently become an enormous challenge for the YRD region. Clarifying the driving factors of CE in the YRD urban agglomeration will not only help China achieve the dual carbon goal as soon as possible but also provide beneficial implications for the design of CE reduction paths in other mega-urban agglomerations.

3.2. Data

Based on the YRD mega-urban agglomeration development plan prepared by the State Council of China, we identify 26 cities, including Shanghai and Nanjing, that form the YRD mega-urban agglomeration. The variables studied include the crop of each industry of each city, GDP, urban production and energy consumption (EC), residents' consumption, urban and rural (U&R) residents' living EC, the U&R

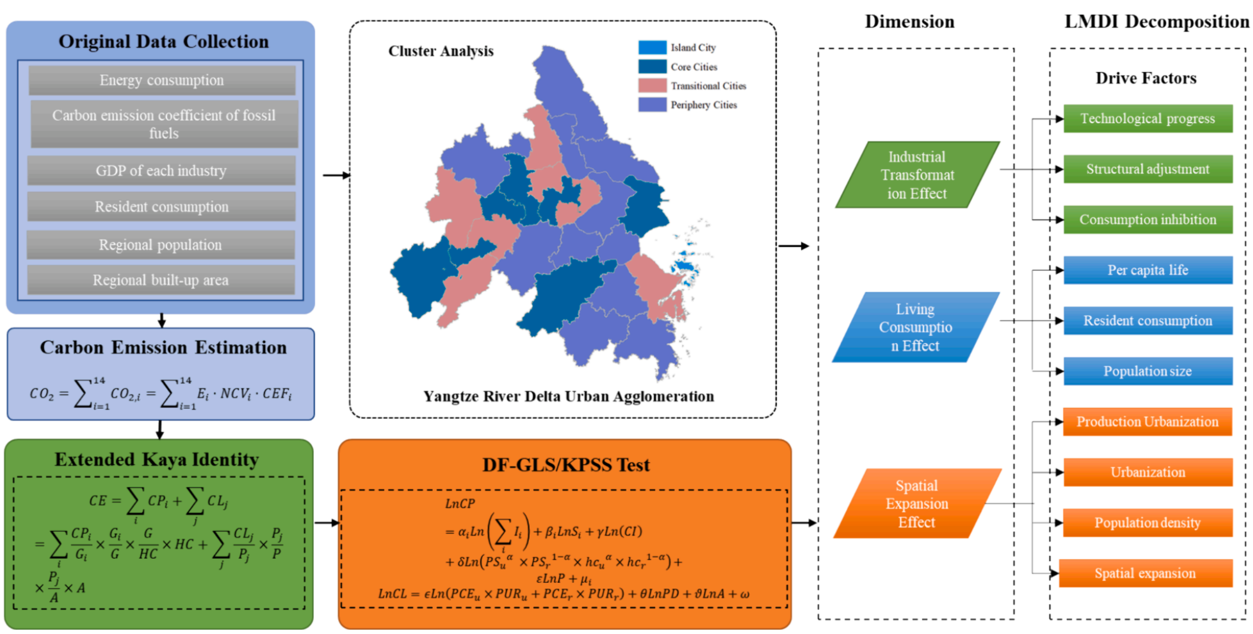

Fig. 2. Research framework.

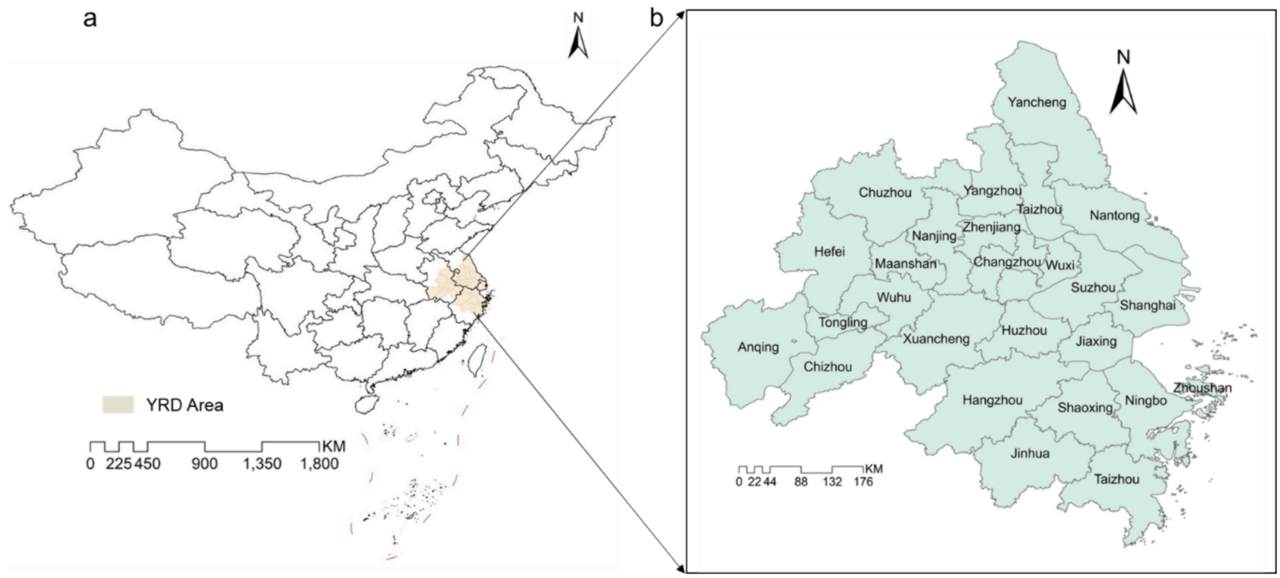

Fig. 3. (a) Location of study area, (b) Overview of YRD urban agglomeration.

population, and the built-up area. The research time span is 2006–2019. These data are from the China Energy Statistical Yearbook, the China Statistical Yearbook, and the statistical yearbook of each city. We convert the nominal output value, nominal GDP and nominal consumption of each industry into the real output value, real GDP and real consumption based on a deflator.

Similar to the existing research(Duren and Miller, 2012), because of the prevalence, measurability and standardization of carbon dioxide and the universality of public discourse in academic circles, we choose carbon dioxide to represent carbon emissions. The Chinese government has not released official sources of CE data. Some research institutions, such as the US Energy Information Administration, have calculated China's CE. However, due to the insufficient accuracy and time coverage of the data that they published, this paper adopts the method provided by the Intergovernmental Panel on Climate Change (IPCC) to estimate the CE of the cities in the YRD based on production EC data and household EC data:

$$CO_2 = \sum_{i=1}^{14} CO_{2,i} = \sum_{i=1}^{14} E_i \cdot NCV_i \cdot CEF_i \tag{1}$$

where CO_2 refers to the carbon dioxide emissions to be estimated; i refers to various energy fuels; E_i represents the combustion consumption of various energy sources; NCV_i is the average low calorific value of various energy sources; and CEF_i refers to the carbon dioxide emission factor of various energy sources. See **S upplement file** for the specific calculation method.

CE intensity in this study is defined as the amount of carbon emissions per unit of economic output, which is a common metric used in sustainability studies to understand the carbon efficiency of an economy (Dong et al., 2018; Pan et al., 2019). The formula for calculating CE intensity: CE intensity $= \frac{\text{Total Carbon Emissions}}{\text{Gross Domestic Product(GDP)}}$.

3.3. Exponential decomposition

The logarithmic mean Divisia index (LMDI) is widely used to quantitatively evaluate the impact of different factors on carbon dioxide emissions. It has no residual, time reversal or factor reversal advantages. Therefore, the LMDI method is applied in the decomposition of urban CE drivers, and it comprehensively reflects the interactive impact of industrial development, consumption behavioral change and spatial land expansion on CE. Referring to the existing research(Ang and Zhang, 2000; Cheng et al., 2023), we divide urban carbon emissions into two categories: production-side carbon emissions and life-side carbon emissions. Based on the transmission mechanism of influencing factors, the following model is constructed:

$$C = CP + CL = \sum_i CP_i + \sum_j CL_j = \sum_i \frac{CP_i}{G_i} \times \frac{G_i}{G} \times \frac{G}{HC} \times HC + \sum_j \frac{CL_j}{P_j} \times \frac{P_j}{P} \times \frac{P_j}{A} \times A \tag{2}$$

where C is total CEs, CP is the amount of C in production ($i = 1$, 2, and 3 represent each industry, respectively), CL is the CE of C in daily life ($j =$ u and r represent urban and rural, respectively), G is GDP, HC is household consumption, P is the number of people, and A is the total area of the study region. Spatial expansion is introduced into the impact of living EC to reflect the impact of the spatial layout on residents' direct living EC. Considering the differences in the U&R dual structure in the YRD's urbanization process, we conduct vector decomposition of residents' consumption as follows:

$$HC = \left(\frac{P_u}{P}\ \frac{P_r}{P}\right) \times \begin{pmatrix} \frac{HC_u}{P_u} \\ \frac{HC_r}{P_r} \end{pmatrix} \times P = (PS_u PS_r) \times \begin{pmatrix} hc_u \\ hc_r \end{pmatrix} \times P \tag{3}$$

where P_u and P_r refer to the urban population and the rural population, respectively, and $PS_u = \frac{P_u}{P}$ and $PS_r = \frac{P_r}{P}$ refer to the proportion of the urban population and the rural population in the total population, respectively. HC_u and HC_r represent the total consumption of urban

Table 1
LMDI additive decomposition results of CE in urban agglomerations.

Type	Effect	Additive decomposition formula
Production end	TE-Technological progress effect	$\sum_i \frac{CP_i^t - CP_i^0}{lnCP_i^t - lnCP_i^0} ln \frac{TP_i^t}{TP_i^0}$
	SE-Structural adjustment effect	$\sum_i \frac{CP_i^t - CP_i^0}{lnCP_i^t - lnCP_i^0} ln \frac{SA_i^t}{SA_i^0}$
	CRE-Consumption inhibition effect	$\sum_i \frac{CP_i^t - CP_i^0}{lnCP_i^t - lnCP_i^0} ln \frac{CI^t}{CI^0}$
	UE-Production urbanization effect	$\sum_i \frac{CP_i^t - CP_i^0}{lnCP_i^t - lnCP_i^0} [\alpha^t lnPS_u^t - \alpha^0 lnPS_u^0 + (1-\alpha^t) lnPS_r^t - (1-\alpha^0) lnPS_r^0]$
	HCE-Resident consumption effect	$\sum_i \frac{CP_i^t - CP_i^0}{lnCP_i^t - lnCP_i^0} [\alpha^t lnhc_u^t - \alpha^0 lnhc_u^0 + (1-\alpha^t) lnhc_r^t - (1-\alpha^0) lnhc_r^0]$
	PE-Population size effect	$\sum_i \frac{CP_i^t - CP_i^0}{lnCP_i^t - lnCP_i^0} ln \frac{P^t}{P^0}$
Living end	LPE-Per capita living effect	$\sum_j \frac{CL_j^t - CL_j^0}{lnCL_j^t - lnCL_j^0} ln \frac{PL_j^t}{PL_j^0}$
	PSE-Urbanization effect	$\sum_j \frac{CL_j^t - CL_j^0}{lnCL_j^t - lnCL_j^0} ln \frac{PS_j^t}{PS_j^0}$
	HDE-Population density effect	$\sum_j \frac{CL_j^t - CL_j^0}{lnCL_j^t - lnCL_j^0} ln \frac{PD^t}{PD^0}$
	AE-Spatial expansion effect	$\sum_j \frac{CL_j^t - CL_j^0}{lnCL_j^t - lnCL_j^0} ln \frac{A^t}{A^0}$

residents and rural residents, respectively; $hc_u = \frac{HC_u}{P_u}$ and $hc_r = \frac{HC_r}{P_r}$ represent the per capita consumption of urban residents and rural residents, respectively. Household consumption is included in the production impact formula to reflect the impact of consumption demand on the indirect CE of producers. In addition, spatial expansion is included in the CE impact formula to reflect the impact of the spatial layout on residents' direct CE. Substituting equation (3) into equation (2) yields the following:

$$C = \sum_i \frac{CP_i}{G_i} \times \frac{G_i}{G} \times \frac{G}{HC} \times (PS_u\, PS_r) \times \begin{pmatrix} hc_u \\ hc_r \end{pmatrix} \times P + \sum_j \frac{CL_j}{P_j} \times \frac{P_j}{P} \times \frac{P_j}{A} \times A \tag{4}$$

Simplify it with symbols as follows:

$$C = \sum_i TP_i \times SA_i \times CI \times (PS_u\, PS_r) \times \begin{pmatrix} hc_u \\ hc_r \end{pmatrix} \times P + PCE_u \times PUR_u \times PD \times A + PCE_r \times PUR_r \times PD \times A \tag{5}$$

where $TP_i = \frac{CP_i}{G_i}$ refers to the CE intensity of industry i and industrial technology development, $SA_i = \frac{G_i}{G}$ refers to the proportion of the GDP of industry i in total GDP, reflecting industrial structure adjustment, and $CI = \frac{G}{HC}$ refers to the ratio of GDP to total household consumption, indicating the degree of consumption inhibition. At the end of life, $PCE_u = \frac{CP_u}{P_u}$ refers to the per capita living CE intensity of cities and towns, $PUR_u = \frac{P_u}{P}$ refers to the urbanization rate, and $PD = \frac{P}{A}$ refers to population density. $PCE_r = \frac{CP_r}{P_r}$ refers to the per capita living CE intensity of rural, and $PUR_r = \frac{P_r}{P}$ refers to the rural rate.

Differential transformation is performed on the production end and life end as follows:

$$d(lnCP) = d\left(ln\sum_i CP_i\right) \doteq d\left(ln\left(\sum_i TP_i \times SA_i \times CI \times {PS_u}^{\alpha} \times {PS_r}^{1-\alpha} \times {hc_u}^{\alpha} \times {hc_r}^{1-\alpha} \times P\right)\right) \tag{6}$$

$$d(lnCL) = d\left(ln\sum CL\right) = d\left(ln\left(PCE_u \times PUR_u \times PD \times A + PCE_r \times PUR_r \times PD \times A\right)\right) = d\left(ln\left((PCE_u \times PUR_u + PCE_r \times PUR_r) \times PD \times A\right)\right) \tag{7}$$

where P_u and P_r represent the number of urban residents and rural residents, respectively, and $\alpha = \frac{PS_u hc_u}{PS_u hc_u + PS_r hc_r}$ and $1 - \alpha = \frac{PS_r hc_r}{PS_u hc_u + PS_r hc_r}$ represent the proportion of total consumption of urban residents and rural residents in the total consumption of residents, respectively. It's worth noting that while our formula may present a conceptual bridge between matrix and product forms, it's not a strict mathematical equivalence. We use the actual statistical data of residents' consumption to show the differences between them. Please refer to S upplement file for details. The impact equation of total CE can be derived as equation (8) and can be decomposed into a dual structure of U&R CE in the process of urbanization.

$$C = \sum_i TP_i \times SA_i \times CI \times {PS_u}^{\alpha} \times {PS_r}^{1-\alpha} \times {hc_u}^{\alpha} \times {hc_r}^{1-\alpha} \times P + (PCE_u \times PUR_u + PCE_r \times PUR_r) \times PD \times A \tag{8}$$

The base period and investigation period are represented by 0 and t respectively(Ang, 2005), and the expression of contribution value of each effect is shown in Table 1. Where PL corresponds to $PCE_u \times PUR_u$, and PS corresponds to $PCE_r \times PUR_r$.

3.4. K-means clustering algorithm

Herbert Hirschman's Unbalanced Growth Theory posits that economic development is most effectively fostered through a deliberate imbalance in the allocation of resources across sectors, rather than a balanced, across-the-board development. With the expansion of the core area of an urban agglomeration, growth in regional inequality is inevitable. To fully explore the spatial heterogeneity in the influencing factors of CE in cities in the YRD mega-urban agglomeration, we cluster the LMDI decomposition results of CE in 26 cities and discuss the characteristics of the CE driving factors of each city in the study period based on the clustering results. We do so to provide targeted CE reduction strategies for the YRD mega-urban agglomeration.

$$LnCIP = \alpha_i Ln\left(\sum\nolimits_i I_i\right) + \beta_i LnS_i + \gamma Ln(CI) + \delta Ln\left(PS_u{}^{\alpha} \times PS_r{}^{1-\alpha} \times hc_u{}^{\alpha} \times hc_r{}^{1-\alpha}\right) + \varepsilon LnP + \mu_i \tag{9}$$

K-means is one of the most commonly used methods of clustering. The algorithm clusters data by separating the samples into groups with equal variance. The more similar the samples are, the smaller the difference is. Finally, multiple clusters are formed. In these clusters, the similarity of the samples within the same cluster is high, and the difference between different clusters is also high. This algorithm can be extended to a large number of samples and has been widely used in many different fields. The inspection steps are as follows:

1) Input the LMDI result sample set of YRD mega-urban agglomeration $X = \{X_1, X_2, \cdots, X_{26}\}$, and determine the number of clusters K.

2) Determine K initial class clusters $C_i(1 \le i \le K)$ and K cluster center vectors $\mu_i(1 \le i \le K)$.

3) For each sample X_j, the cluster center μ_i and Euclidean distance d_{ij} are calculated. Divide the samples into the nearest cluster.

4) Recalculate the clustering center vector of K clusters $\mu_i = \frac{\sum_{x \in C_i} X}{|C_i|}$.

5) Repeat steps 3) to 4) until each cluster center vector does not change.

Because the number of groups selected by the clustering method is subjective, using the elbow method (see **S upplement file**) makes it possible to find the value of the change in distance between clusters with the largest curvature and then optimize the number of groups. We use R to achieve this operation.

Table 2
Overall contribution of CE drivers in the YRD, 2006–2019.

Type	Effect	Total emissions/ million tonnes	Proportion/ %
Production end	TE-Technological progress effect	−10.42	−2.55
	SE-Structural adjustment effect	−72.66	−17.59
	CRE-Consumption inhibition effect	−111.17	−26.91
	UE-Production urbanization effect	45.54	11.03
	HCE-Resident consumption effect	473.97	114.73
	PE-Population size effect	94.38	22.85
Living end	LPE-Per capita living effect	0.046	0.01
	PSE-Urbanization effect	−18.32	−4.44
	HDE-Population density effect	−18.32	−4.44
	AE-Spatial expansion effect	30.37	7.35

3.5. Long-term equilibrium relationship test

Here, we discuss the long-term equilibrium relationship between CE and the industrial structure, per capita consumption, population and space. Based on equation (8), the CE at the production end and the living end can be divided into the industrial structure, technical intensity, consumption inhibition, U&R consumption, population density and the urban spatial effect. To convert the nonlinear relationship into a linear structure, we take natural logarithms on both sides of equation (8) to obtain the following formula:

$$LnCIL = \epsilon Ln(PCE_u \times PUR_u + PCE_r \times PUR_r) + \theta LnPD + \vartheta LnA + \omega \tag{10}$$

Analyzing $LnCIP$, $Ln(\sum_i I_i)$, LnS_i, and $LnPC$, we use Stata to test the unit root based on the test results of DF-GLS and KPSS. (see **S upplement file**). The results of the analysis report that all time series data are stable. In addition, equations (9) and (10) contain residuals, and we set the contribution of population growth to CE intensity to include the residual term.

4. Results

4.1. Overview of the three-stage development history of CE in the YRD city cluster

The decomposition results of the CE effects from 2006 to 2019 are shown in Table 2 and Fig. 4. From 2006 to 2019, the carbon dioxide emissions of the YRD mega-urban agglomeration increased from 336.98 million tonnes to 746.26 million tonnes, an increase of 409.28 million tonnes. The annual rate of increase was approximately 11 %, of which the growth rate of carbon dioxide at the production end was 4.6 times that at the living end (Table 2).

The cumulative contribution of CE at the production end was 415.8 million tonnes, and the cumulative contribution of CE at the living end was −6.52 million tonnes. Based on the overall trend of the total CE of the YRD mega-urban agglomeration shown in Fig. 4, the LMDI results can be summarized into the following three periods. For the error analysis of this part, please refer to the S upplement file.

In the first stage (2006–2016), the total carbon emissions (CE) of the YRD displayed a fluctuating increase from 336.98 million tonnes to 459.36 million tonnes. This period was marked by a significant growth in infrastructure investment and marketization, positioning the YRD as a key player in international manufacturing. Despite the impact of the international financial crisis between 2008 and 2009, the region's economy demonstrated resilience and recovery, partly due to a substantial market rescue policy. The total industrial output value of six cities in the YRD mega-urban agglomeration surpassed 1 trillion yuan, contributing to the rebound in CE levels, which eventually exceeded pre-crisis figures.

During the second stage (2016–2018), a notable surge in CE within the YRD was observed, primarily driven by an increase in primary energy consumption (EC). The region's EC rose by 3.1 %, with oil consumption growing by an average of 1.8 % and coal consumption by 1.5 %, the first rise since 2013. Consequently, the total CE of the YRD mega-urban agglomeration showed a marked increase in 2018, with the

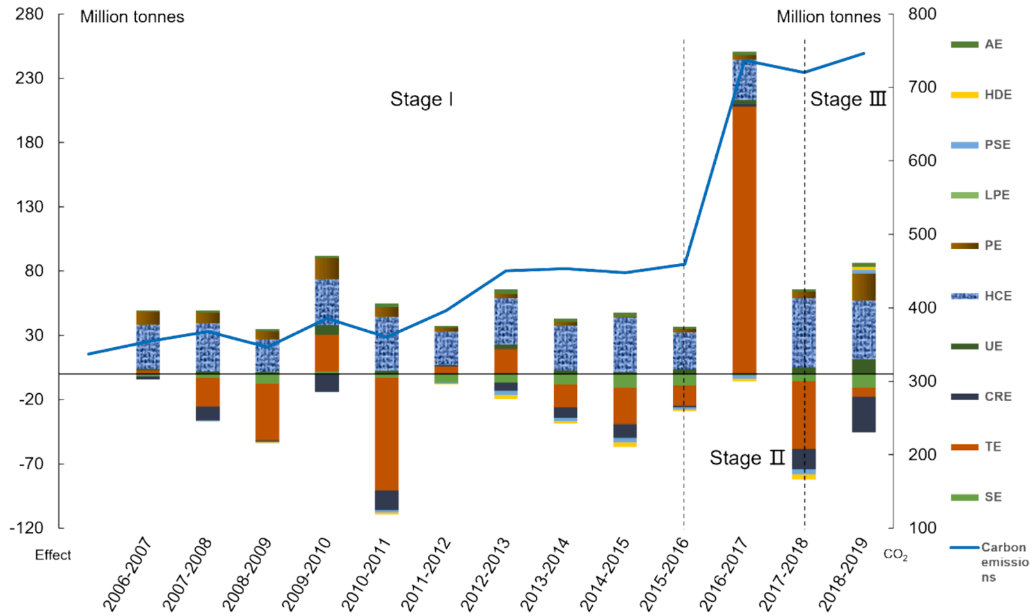

Fig. 4. Comprehensive impact of CE drivers, 2006–2019. The broken line shows the annual change of carbon emissions, and the stacked column chart shows the proportion of driving factors of carbon emissions.

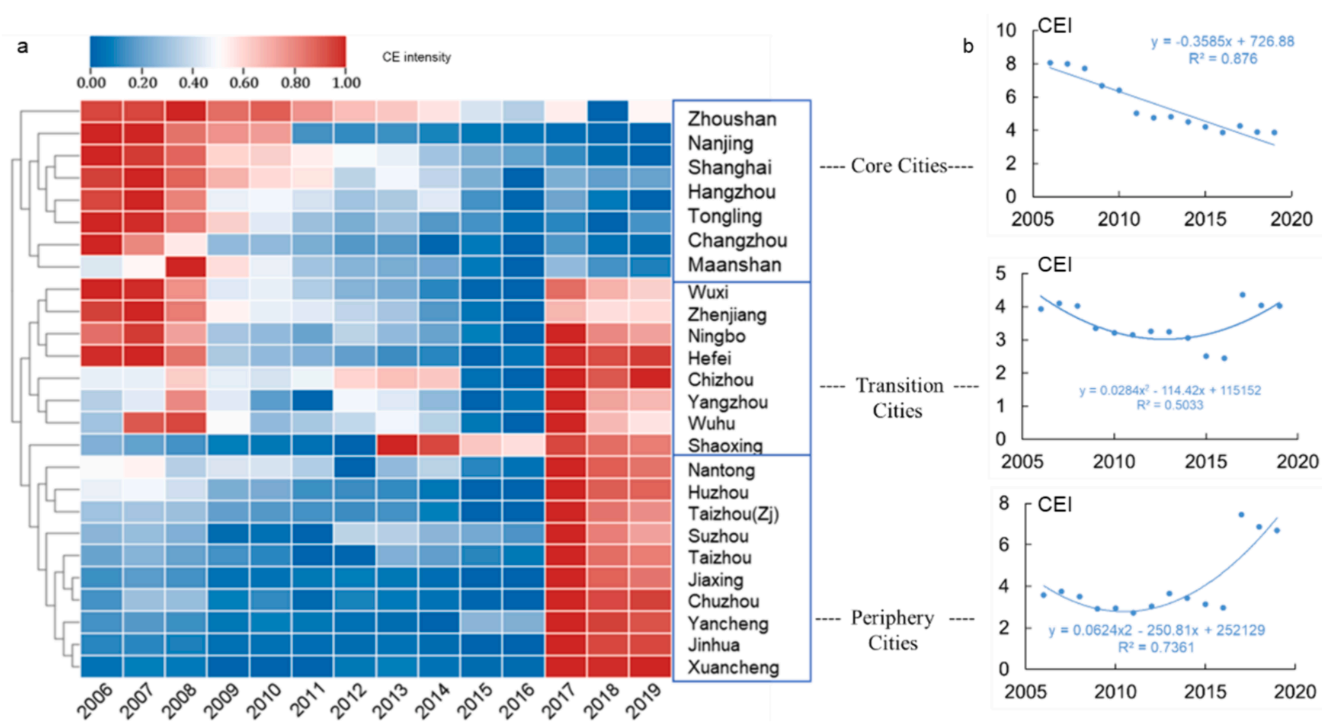

Fig. 5. Cluster analysis of the CE intensity of the YRD mega-urban agglomeration. (a) indicates that the CE intensity of cities changes year by year, the normalized CE intensity is used to draw a heat map, with the blue part indicating the lower CE intensity and the red part indicating the higher carbon emission intensity. And (b) indicates the fitting curves of the carbon emission intensity changes of three groups of cities, The vertical axis represents the carbon emission intensity and the horizontal axis represents the year. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

growth in industrial CE intensity being a significant contributor to this rise.

In the third stage (2018–2019), the YRD's development was further boosted by its elevation to a national strategy. The integration of regional input factors led to the industrial value added in the YRD surpassing the national average. The total GDP of major cities such as Shanghai, Nanjing, Wuxi, Suzhou, Hangzhou, and Ningbo exceeded 1 trillion yuan. This period also saw a widening gap between the residents' disposable income in the YRD and the national average, accompanied by an 8.2 % increase in fixed asset investment. As a result, the total CE of the YRD during this period continued to increase steadily.

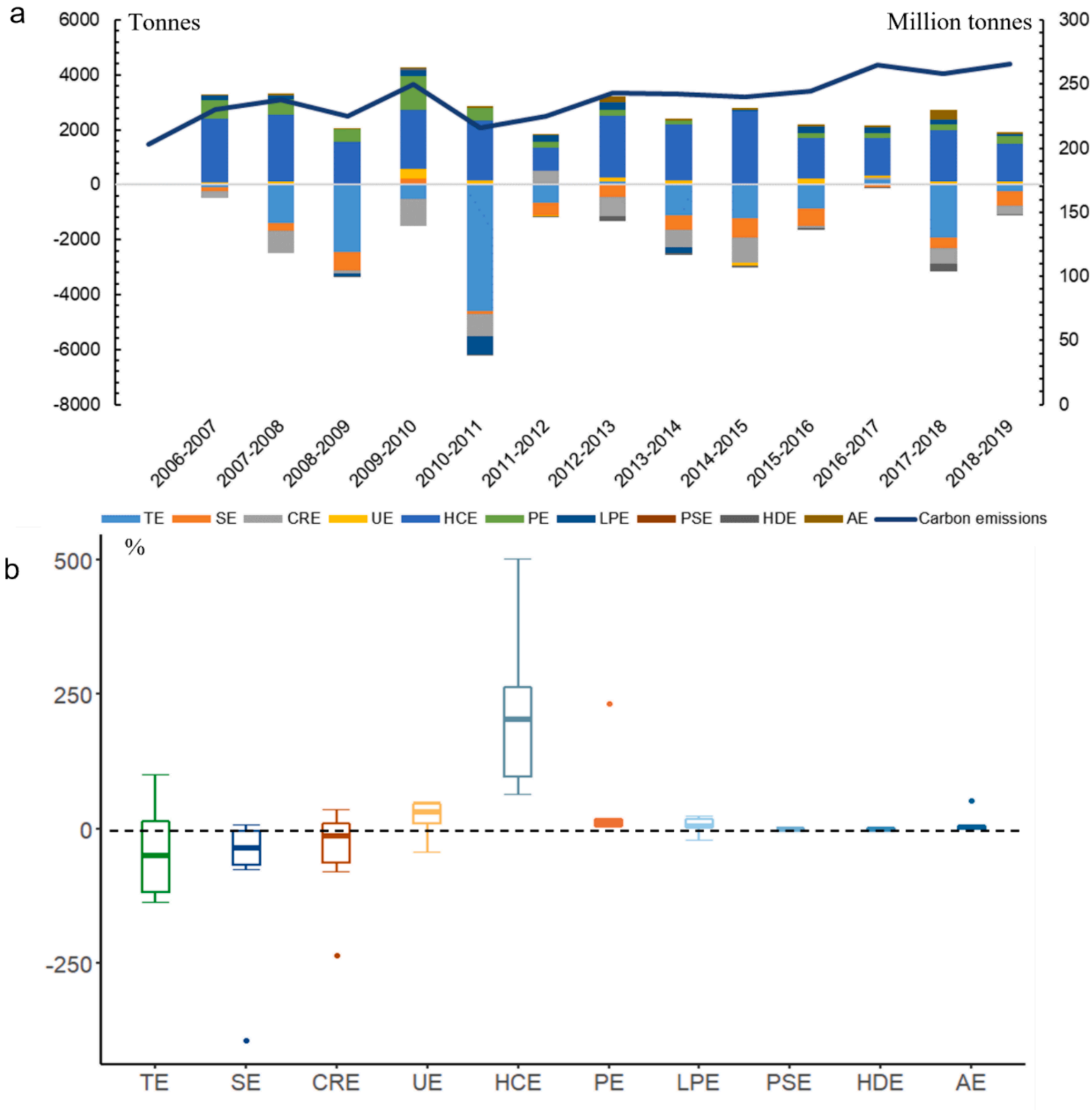

Fig. 6. (a) The line represents the annual change of total CE, and the stacked column chart represents the specific contribution of CE driver factor every two years. (b) The box chart represents the change of contribution ratio of each CE driver factor, dots represent outliers, indicating extreme values beyond the typical range, the same applies to the following figures.

4.2. Heterogeneity analysis of CE drivers in cities with carbon intensity grouping

As shown in Fig. 5, the CE intensity of the cities in the YRD during the 2006–2019 period can be divided into three groups.

The change in CE intensity in the core cities is characterized by a continuous decrease, realizing the initial decoupling of the economy and CE. The development degree of transitional cities is slightly weaker than that of core cities. The change in CE intensity in transitional cities is characterized by a decreasing and then an increasing trend, showing a U-shaped feature. Peripheral cities are the least developed among the YRD cities (except Suzhou), and their CE intensity is characterized by a decreasing and then an increasing trend. The difference from transitional cities is that their CE intensity increases faster. Suzhou's classification as a peripheral city based on carbon emission intensity, despite its strong economic development, can be attributed to several factors during the study period. Firstly, Suzhou's economy has historically relied heavily on manufacturing and industrial activities, which are typically high in energy consumption and carbon emissions. Even with economic growth, if the industrial sector remains energy-intensive, carbon emission intensity may remain high(Si et al., 2023). Secondly, Rapid urbanization and population growth in Suzhou can contribute to increased residential energy consumption, transportation emissions, and construction activities, all of which add to the city's carbon footprint (Wang et al., 2014). Last but not least, the reliance on fossil fuels for energy needs in Suzhou remains a significant issue. While there have been efforts to incorporate renewable energy sources, the transition has been gradual, and fossil fuels still dominate the energy mix(Sun et al., 2022).

4.2.1. Core cities

Core cities are the first-tier cities in the YRD, and they include

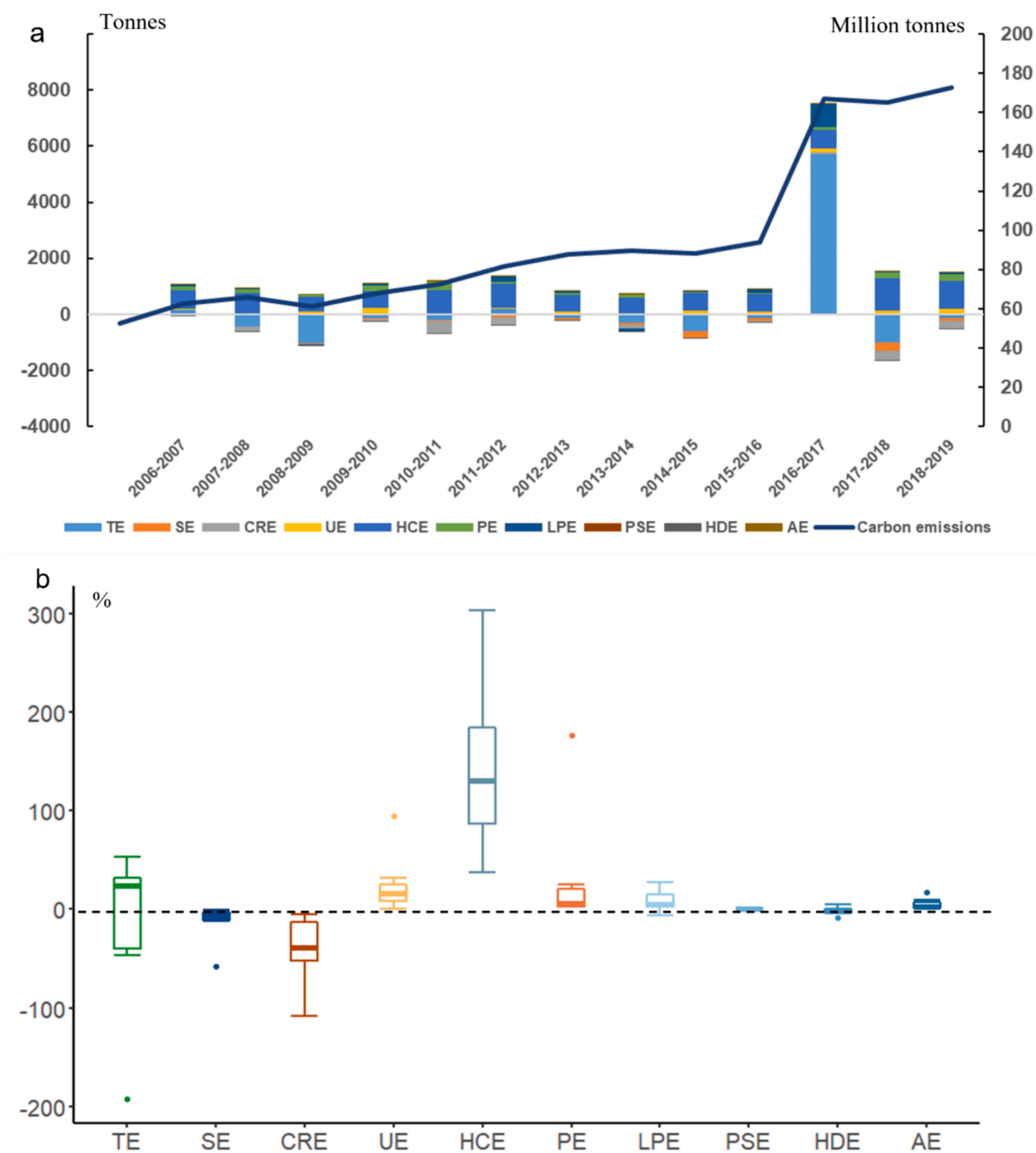

Fig. 7. (a) The line represents the annual change of total CE, and the stacked column chart represents the specific contribution of CE driver factor every two years. (b) The box chart represents the change of contribution ratio of each CE driver factor.

Shanghai, Nanjing and Hangzhou. Based on the clustering results and Fig. 6a, although the total CE of core cities have increased slightly year by year, the overall CE intensity has decreased year by year. Among the positive drivers of CE, the resident consumption effect still accounts for the greatest contribution (Fig. 7). Due to the significant increase in residents' disposable income brought by the vigorous economic development in the YRD in the past 10 years, the consumption upgrading and quality of life improvement brought by the increase in the income of low-income groups have produced more CE. Furthermore, the gray EC of residents in the YRD has increased significantly in recent years. The negative drivers of CE from core cities are mainly the industrial technology effect, industrial structure effect and consumption inhibition effect.

4.2.2. *Transitional cities*

Throughout the investigation period, the primary positive driving factors for carbon emissions (CE) in transitional cities within the Yangtze River Delta (YRD) were identified as the resident consumption effect, population effect, and per capita living effect. Notably, transitional cities have experienced substantial net population inflow,

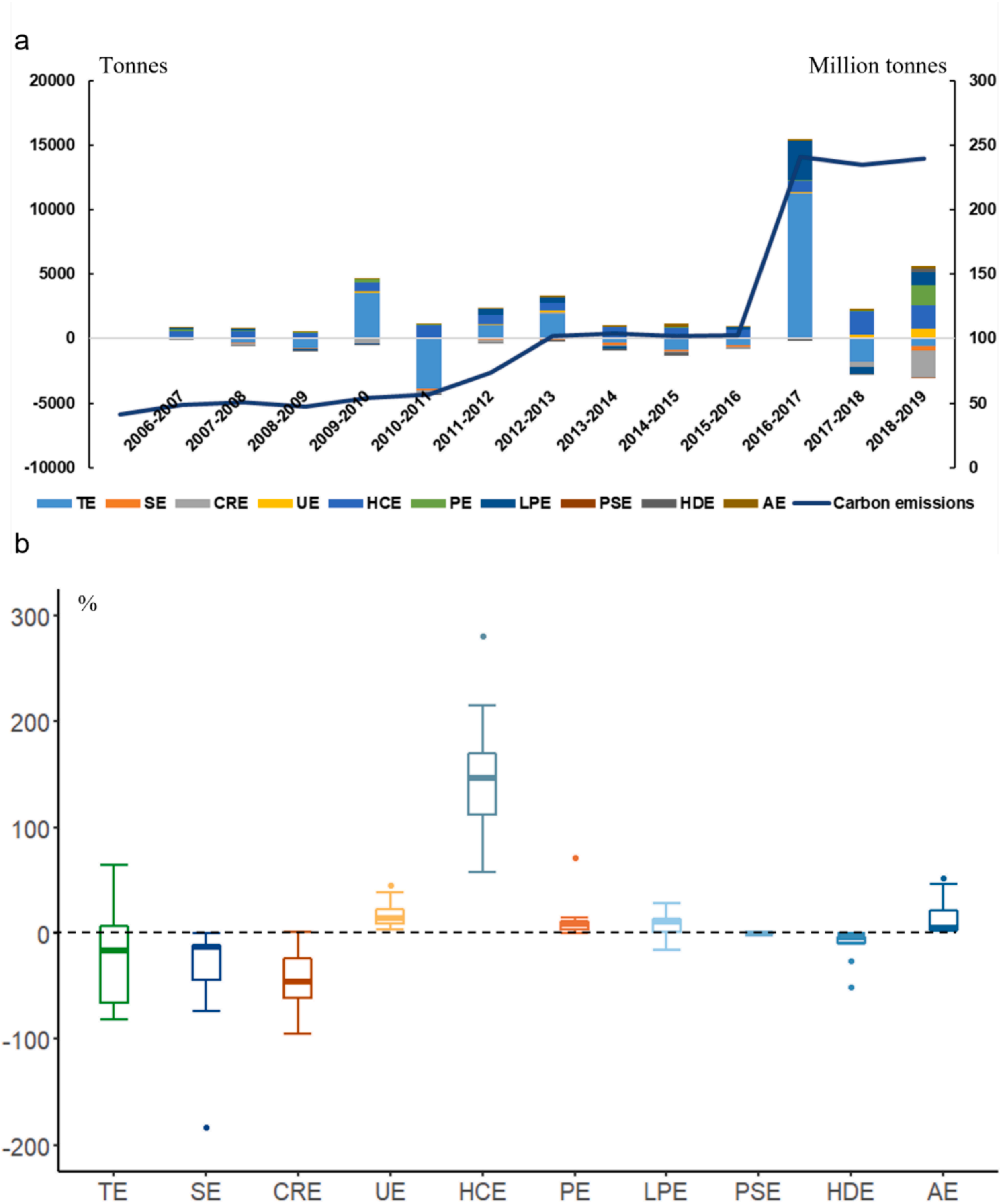

Fig. 8. (a) The line represents the annual change of total CE, and the stacked column chart represents the specific contribution of CE driver factor every two years. (b) The box chart represents the change of contribution ratio of each CE driver factor.

significantly influencing CE through the population and per capita living effects. In 2017, a marked rebound in CE was observed, predominantly attributed to an increase in factory numbers in the YRD. This industrial expansion led to a 3 % increase in coal consumption and a 5 % rise in oil consumption. Such changes highlight the impact of industrial development and energy use patterns on regional CE trends. Conversely, the negative drivers impacting CE reduction in transitional cities were predominantly found to be the consumption inhibition effect, the industrial technology effect, and the industrial structure effect. These factors collectively suggest a shift in both consumption patterns and industrial practices towards more sustainable and less carbon-intensive approaches.

4.2.3. *Peripheral cities*

The area of peripheral cities accounts for approximately half of the YRD region, and it is composed of 11 newly developed cities. Regarding

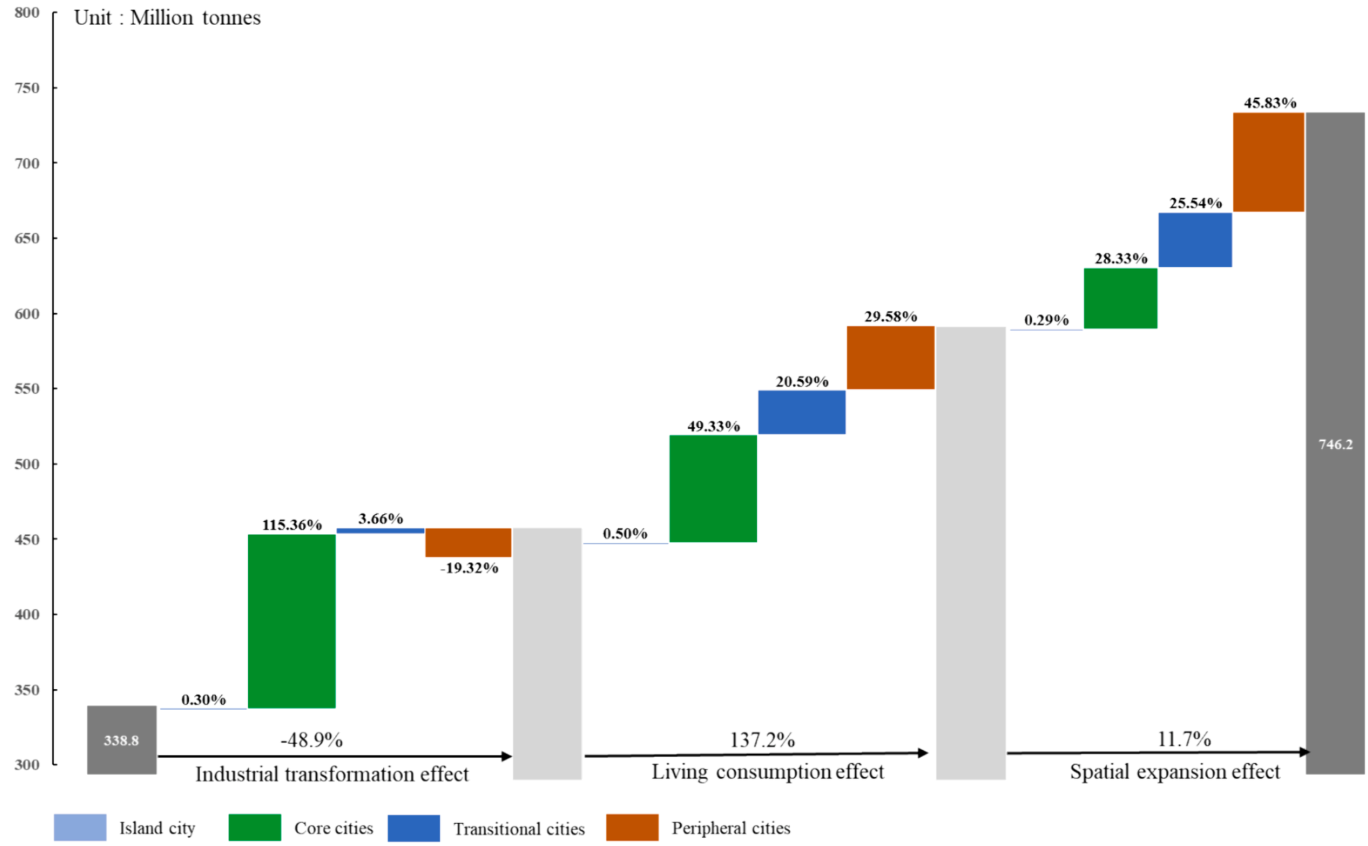

Fig. 9. Comprehensive analysis of the proportion of carbon emission changes from 2006 to 2019 in the YRD urban agglomeration due to industrial transformation, living consumption, and spatial expansion*.**For the sake of analysis, Zhoushan, the only island city in our YRD mega-urban agglomeration, is listed in a separate group.*

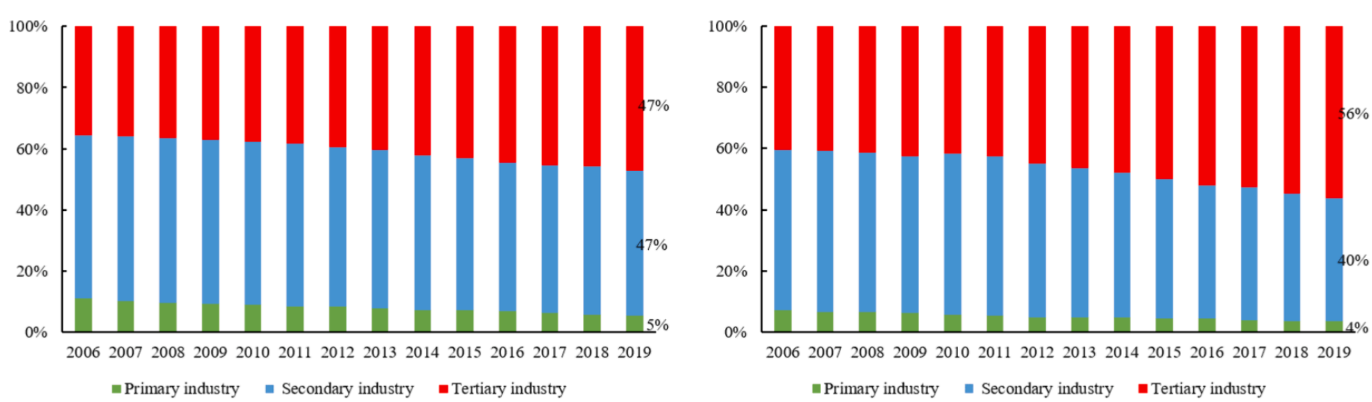

Fig. 10. Composition of the output values of the three industries of core cities and peripheral cities.

the positive driving factors of CE, the industrial technology effect, resident consumption effect and per capita living effect are the main factors driving CE (Fig. 8a). Fig. 8b shows that the increase in CE caused by the unhealthy industrial structure in this region has been reversed and that the consumption inhibition effect and industrial structure effect became the main factors in reducing CE in this region in the 2018–2019 period.

4.3. Multidimensional analysis of CE drivers

Here, we examine the changes in CE for each subgroup of cities from three dimensions, i.e., industry, consumption and space, from a macro perspective (Fig. 9). Industrial transformation includes TE, SE and CRE, living consumption includes LPE, HCE and PE, and spatial expansion includes UE, PSE, HDE and AE. In general, during the study period, industrial transformation effect (including technological change effect and industrial structure effect) changes in the YRD mega-urban agglomeration had a negative impact on CE (−48.9 %) and living consumption effect (137.2 %) and spatial expansion (11.7 %) were the positive drivers of the CE of the YRD mega-urban agglomeration.

In the YRD mega-urban agglomeration, market consumption has emerged as the largest contributor to the net growth in CE. Core cities, which cover about one-third of the region, are responsible for approximately half of the regional CE. This is particularly evident in developed cities like Shanghai, Nanjing, and Hangzhou, where the rapid development of secondary and tertiary industries over the past decade has attracted a significant influx of nonlocal people. This migration has led to an increase in the income levels of local permanent residents, enhancing their consumption capacity. The combined effect of an expanding population and increased per capita consumption has led to a rise in energy consumption (EC), consequently elevating the regional CE. This trend aligns with observations that in China's coastal developed provinces, domestic EC is becoming the primary carbon source. The shift in rural areas towards more mechanized agriculture, marked by increased usage of large agricultural machinery and equipment, has further contributed to the rise in fuel consumption, particularly diesel. As a result, agricultural machinery's greenhouse gas emissions in the YRD have surpassed those of road vehicles, underscoring the need for strategies to control agricultural emission sources. In transitional cities within the YRD, apart from Ningbo, the CE due to residents' consumption exceeds half of the total production-end CE. This indicates that the concept of low-carbon consumption is yet to be widely internalized, with the existing consumption structure characterized by high CE and high EC. This suggests a substantial potential for demand-side CE reduction. Peripheral cities, as less developed regions within the YRD mega-urban agglomeration, are experiencing rapid economic growth. In these areas, the largest components of residents' total consumption are housing, transportation, and communication. To achieve the goal of CE reduction, there is a need for a focus on green housing and low-carbon infrastructure development.

Regarding the industrial structure and industrial technology, island cities, transitional cities and peripheral cities have achieved the goal of CE reduction. As one of the most developed regions in the YRD mega-urban agglomeration, core cities entered the post-industrialization period when per capita GDP exceeded 70,000 CNY in 2012, taking the lead in entering the development and transformation period in the YRD mega-urban agglomeration. The changes in the proportion of the three industries of core cities are shown in Fig. 10. By the end of this research period, the secondary industries of Nanjing, Shanghai and Hangzhou, including new energy vehicles, industrial robots and integrated circuits, were the main industries. These industries are characterized by intelligence, greenness and high value added. Therefore, at the industrial level, core cities have achieved a preliminary decoupling between CE and economic development. The output value of the three industries of transitional cities accounts for 36.5 % of the total output value of the YRD mega-urban agglomeration, and the contribution of industrial CE reduction is 3.66 %. Therefore, transitional cities have great potential for industrial CE reduction, and they need to maximize the effectiveness and optimize the efficiency of resource allocation based on market mechanisms. By promoting CE trading and contract energy management, a large number of low-cost and negative-cost CE reduction schemes can be fully exploited to obtain the maximum CE reduction benefits. As shown in Fig. 10, the secondary industry of peripheral cities still occupies the main position in the economy, and high-CE and high-EC industries such as the steel, electronic device manufacturing, and chemical manufacturing industries account for a relatively high proportion. Therefore, peripheral cities are the only city cluster in the YRD that positively drives CE in terms of the industrial structure and technology. Adjusting the industrial structure and achieving technological progress are the top priorities of this city group.

Regarding industry, we should pay attention to the green synergy of industrial development between core cities and surrounding cities to avoid pollution havens. Transitional cities and marginal cities should take advantage of the diffusion effect of core cities to achieve dislocation development, avoid industrial homogenization, pay attention to the development of ecological industries and strengthen their ecological CE reduction function while maintaining the fundamentals of their own economic development. Notably, island cities have important development potential in terms of marine carbon sequestration, and we should pay attention to the construction of the ecological carbon sequestration industry.

5. Discussion

5.1. Extended explanation of the change of driving factors of CE in cities

5.1.1. Core cities

The main reason for the formation of positive CE drivers in core cities is that the significant increase in residents' disposable income brought by the vigorous economic development in the YRD in the past 10 years, the consumption upgrading and quality of life improvement brought by the increase in the income of low-income groups have produced more CE. Furthermore, the gray EC of residents in the YRD has increased significantly in recent years. The negative driving factors of CE in core cities correspond to backwash effect proposed by Karl Gunnar Myrdal (Westlund, 2020). Shanghai, Nanjing and Hangzhou, the three core cities, have gradually transferred high-EC and high-CE industries and attracted capital inflows and trade activities from other regions based on their own resource endowment, regional advantages and existing development level. Clearly, the optimization of the economic structure and the reduction in the gap between rich and poor groups and between urban residents and rural residents had a significant positive role in realizing CE reduction goals.

At the same time, the consumption expenditure ratio of U&R residents decreased from 2.17:1 in 2016 to 1.84:1 in 2019, showing that the U&R income gap is decreasing (Fig. 11). In addition, in recent years, Engel's coefficient of U&R households has been approximately 0.36, which is significantly lower than 0.49 in 2000. However, there is still much room for improvement, given that it is approximately 0.2 in European countries and the United States. It can be predicted that household consumption will become the main factor promoting indirect EC in the future: the increase in the disposable income of rural residents will bring greater demand for durable consumer goods (such as household appliances, cars, and computers) (Wei et al., 2007). Furthermore, the demand for services will rise due to the change in the consumption composition of urban residents(Dou et al., 2021). The population effect is also the main driver of CE and shows a U-shaped change trend, mainly due to the loosening of the family planning policy that had been

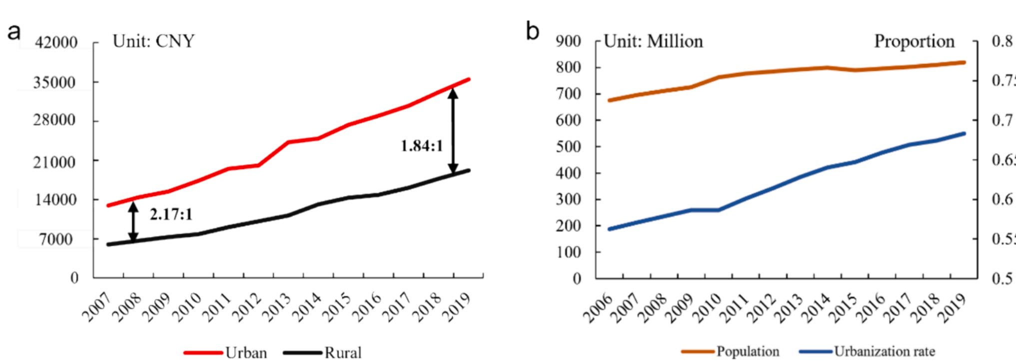

Fig. 11. (a) U&R per capita consumption, (b) Average population and urbanization rate of core city groups.

maintained for decades. In 2016, the Chinese government issued a two-child policy to stimulate people's willingness to have children. The increase in population provides a broader consumer market, which in turn provides a stronger driving force for CE. Chen et al. (2022)further predicted that the two-child policy will increase China's total EC by 16.2 % in 2050, which will greatly hinder the achievement of the dual carbon goal on schedule.

5.1.2. Transitional cities

Positive drivers of CE in transitional cities are due to the close integration of industries and markets in cities such as Wuxi and Hefei and the high degree of integration of production, marketing and supply, the carbon dioxide emissions in transitional cities mainly stem from residents' domestic EC and the embedded CE of consumer goods. In addition, the private economy in this region is developed. According to Zhang et al. (2022), Wuxi and Ningbo are important towns in China's national industry and township industry, and the local industrial formats attract labor more easily. According to the theory of the diffusion effect, transitional cities are located around a core city. With the improvement in the infrastructure of the core city, they will obtain technologies and talent from the central area and gradually catch up with the central area.

The reasons for the formation of the positive driving factors of CE in transitional cities are the Chinese government issued the regional planning outline for the YRD region, the region has successively promulgated a number of industrial technology policies, coupled with the addition of a large urban population and high-quality labor during the study period, and the enormous emerging markets formed a market mechanism effect. As a result, the transformation and upgrading of traditional EC resource-based industries and technological upgrading have promoted energy use efficiency and reduced CE intensity. Therefore, continuing to tap the potential of demand-side CE reduction will help transitional cities achieve CE reduction goals.

5.1.3. Peripheral cities

The reason why the positive drivers of CE in peripheral cities are formed is that, in recent years, while the YRD has achieved rapid economic growth, the rapid promotion of industrialization and construction land in these emerging cities has promoted a continuous increase in EC demand. In particular, peripheral cities mostly rely on high-CE industries such as the equipment manufacturing, metallurgy, textile and chemical industries as important economic support, and the industrial structure of most cities is still dominated by the secondary industry. At the same time, due to underdeveloped industrial production technology, there are many industries with high EC, high CE and low efficiency, and the dependence on fossil energy is strong. Therefore, the rapid development of these industries not only improves the living standards of residents but also increases the intensity of urban CE. The negative driving factors of carbon emissions in peripheral cities may be due to the Chinese government has implemented the YRD ecological green integration development strategy and eliminated backward high-EC and high-CE industries. Nantong, Huzhou, Jinhua and other cities proposed action plans for the intelligent transformation and digital transformation of the manufacturing industry to promote the development of a circular economy.

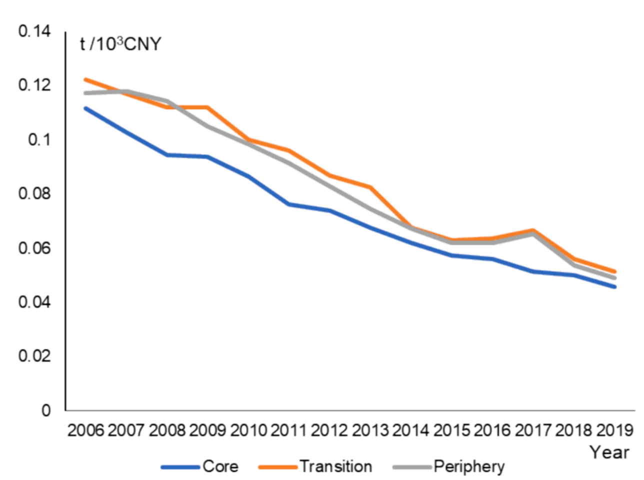

Fig. 12. Ratio of per capita consumption to carbon emissions in three groups of cities. The vertical axis represents the ratio of carbon emissions to per capita consumption, and the horizontal axis represents the annual change.

5.2. Methodological innovations and implications

Previous studies have used LMDI to evaluate the changes of driving factors of carbon emissions in China during the five-year plan and other special policy periods (Yang et al., 2021), but they did not take into account the differences in carbon emissions between urban and rural areas. We introduced the urban–rural dual structure to expand their research methods. Our study employs the combination of the LMDI and urban cluster analysis based on the Kaya identity extension. This innovative approach enables a more comprehensive and precise identification of CE drivers and aids in the design of targeted CE reduction strategies. Particularly, the inclusion of the dual structure of urban and rural areas can lead to a more accurate understanding of the impact of population urbanization changes on CE. Overall, our study presents an in-depth analysis of CE drivers in China's prominent YRD mega-city cluster, setting the stage for effective, targeted policy interventions to drive down carbon emissions in the future.

5.3. New perspectives on CE and control mechanism of urban agglomeration

This study advances the understanding of the drivers of CE by adopting a novel methodological approach and offering unique perspectives. Where Xu et al. (2016) concluded that economic growth was the primary influence on increasing CE and the energy structure had minor impact, the dynamics of time have demonstrated alternative realities. In the context of the YRD region, our findings indicate that the negative contributions of the low carbon production technology and industrial structure improvements to regional CE has hit −48.9 %. Meanwhile, the influence of residential consumption on CE has escalated to 137.2 %.

This disparity in CE growth presents a novel foundation for policymakers to devise CE reduction strategies with a stronger emphasis on consumption(Razzaq et al., 2021). In addition, our results suggest that consumption in core cities tends to be more low carbon in nature when compared to transitional cities and periphery cities (Fig. 12). The reasons behind this may be multiple, including but not limited to, more advanced infrastructure, policy initiatives, and awareness campaigns promoting sustainable consumption habits(Wang et al., 2020). Thus, understanding the ways in which these practices are implemented and successful in core cities could provide valuable insights for enhancing sustainability in transitional cities and periphery cities.

5.4. Role of income Equality, labor inflow in CE management

Furthermore, our analysis suggests that reducing income inequality could serve as an effective strategy towards achieving carbon neutrality. Given the correlation between higher income levels and sustainable consumption practices, promoting economic balance could help drive down overall CE (Zhang et al., 2021). In terms of secondary cities, our study enriches the conclusions of Hu et al. (2022), demonstrating that the significant inflow of labor is a major contributor to CE, primarily due to income and technology effects. For peripheral cities experiencing increased carbon intensity, our analysis proposes the development of a circular economy and strengthened digital infrastructure. Collaboration with surrounding cities in these sectors could effectively curb high CE and mitigate the limitations of previously studied research areas.

Reflecting on the outcomes of our study, it is essential to acknowledge its limitations, which not only provide context to our findings but also point towards avenues for future research. Firstly, the exponential decomposition model used in our study, while robust, lacks strict mathematical equivalence in the matrix and product form, especially considering the urban–rural dual structure. Moreover, our reliance on city-level data, due to the unavailability of more detailed county-level data, suggests that our analysis could be further refined. Lastly, considering the dynamic spatial mobility of industry, population, consumption, and carbon emissions, future research could fruitfully explore the synergistic factors of carbon emission reduction among cities.

6. Conclusions and recommendations

This research offers valuable insights into the impact of industrial transformation, consumption upgrading, and spatial expansion on CE in China's YRD mega-urban agglomeration. Using data from 2006 to 2019, the study considers the dual structure of urban and rural residents' consumption to examine these impacts. The primary conclusions are,

(1) The cities within the YRD mega-urban agglomeration have diverse levels of development, leading to varied CE reduction trajectories.

(2) Market consumption by residents has emerged as the principal driver of CE in the YRD, followed by spatial expansion, with industrial transformation and upgrading counterbalancing some of the CE.

(3) The development of the YRD mega-urban agglomeration shows a marked core-periphery structure, with CE reduction mainly contributed by core cities but accompanied by a CE overflow to transitional and peripheral cities.

Based on the findings of the study, we make the following recommendations.

(1) Implement subsidies and tax incentives for industries that adopt energy-efficient technologies, focusing on sectors identified as major carbon emitters in the YRD. Recognizing the YRD's industrial composition and its significant carbon footprint is essential. This research highlights the need to target high-emission sectors for technological upgrades. Financial mechanisms such as subsidies and tax incentives aim to lower economic barriers to adopting such technologies. Importantly, these incentives should scale with the level of emissions reduction achieved, promoting not only adoption but also continuous environmental performance improvement.

(2) Develop and expand low-carbon public transportation networks in core and peripheral cities to reduce reliance on private vehicles, addressing the spatial expansion's contribution to carbon emissions. Investing in green public transit options, like electric buses and metro systems in both core and peripheral cities, offers accessible, sustainable alternatives to car travel.

(3) Supporting a shift in consumer behavior is paramount to address the significant impact of residential consumption on carbon emissions, as identified in our research. This involves incentivizing low-carbon choices and cultivating an informed public aware of the environmental stakes. Educational campaigns are crucial, providing insights into individual contributions to carbon footprints and actionable steps for reduction. These initiatives should be locally tailored to resonate with the YRD's socio-economic and cultural contexts, fostering a community-wide commitment to sustainability.

(4) Embedding sustainability principles into urban planning policies ensures that strategies are tailored to the unique environmental and socio-economic contexts of the YRD's diverse cities, contributing positively to carbon reduction. Emphasizing the development of green spaces and the use of renewable energy in building projects caters to the unique needs of the YRD's diverse city types.

CRediT authorship contribution statement

Changgao Cheng: Writing – original draft, Methodology, Conceptualization. **Xiang Yan:** Methodology, Formal analysis. **Zhou Fang:** Formal analysis, Data curation. **Qin Zhou:** Project administration, Methodology. **Yan Tang:** Validation, Supervision. **Nan Li:** Visualization, Validation, Resources. **Deshan Tang:** Supervision, Investigation, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2024.112336.

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