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The evolution of carbon footprint in the yangtze river delta city cluster during economic transition 2012-2015

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ABSTRACT

China has been undergoing an industrial transformation, shifting from an energy-intensive growth pattern. As the most developed region in China, the Yangtze River Delta (YRD) city cluster is leading the industrial transformation. However, the impact of the industrial transformation on carbon footprints in the YRD cities is unclear. By a city-level environmentally extended input-output model, we quantify the carbon footprint of 41 cities in the YRD city cluster for 2012 and 2015 and capture the socioeconomic driving forces of the change by structural decomposition analysis (SDA). The results show that the carbon footprint in 41 YRD cities increased from 1179.4 Mt (14.8% of China's total) to 1329.6 Mt (16.6%) over the period. More than 60% of the footprint concentrated on the 10 largest cities, and the construction sector made the largest contribution, especially in service-based megacities. The change of production structure drove down carbon footprints in YRD cities, except light industry cities and service-based cities. The industrial transfers from the coastal to inland regions result in carbon leakage, where one-third of the carbon footprint is embodied in the trade. We also find the economic recession during the transition period decreased carbon emissions by 154.2 Mt in the YRD city cluster, where the value-added rate in the YRD cities declined over the transition period, especially in service-based cities. The study highlights the positive effects of industrial transformation on low carbon transition, despite being highly heterogenous for cities.

1. Introduction

After the 2008 financial crisis, China entered a new stage of economic transition, formulated as a "new normal", in which the economic development model shifted from rapid and extensive growth to slower and high-quality growth (Bai et al., 2021; Mi et al., 2018; Zheng et al., 2020). China's gross domestic product (GDP) growth kept an averagely of 10% over the past 30 years, but fell to 8% in 2012, and then below 7% in 2016. In the new normal era, China prioritized environmental sustainability and the low carbon society by developing clean energy and cleaning the energy mix (Green and Stern, 2016). The change is facilitated by industrial transformation where the industrial structure is expected to be transformed from low value-added to high value-added manufactories.

Industrial upgrading aims for coordinating the economy and the environment (Song, 2019; Zhang et al., 2014). Simultaneously, cities are major contributors to 75% of greenhouse gas emissions (Gouldson et al., 2016), and play an increasingly important role in carbon mitigation (Shan et al., 2018a). How the industrial transformation reshapes carbon emissions in cities largely determines China's low carbon pathway.

The Yangtze River Delta (YRD) city cluster is one of the most economically developed regions in China and has undergone massive industrial transformation (Shao et al., 2019). The YRD city cluster includes 41 cities in four provinces (namely, Shanghai, Jiangsu, Zhejiang, and Anhui), which while covering only 4% of the land area in mainland China, is home to 16% of the population, but produces 24% of GDP and 17% of carbon emissions (Shan et al., 2020). Due to expensive labour prices and land rent, the YRD city cluster undergoes the industrial

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transformation, where industries with low value-added are either eliminated or relocated to other regions with bearable costs (Zheng et al., 2013; Zhu and Zhang, 2021). This reshapes the industrial structure and the inter-city supply chains and consequently affects the pattern of carbon emissions in the YRD city cluster.

Previous studies explored the impact of industrial transformation on carbon emissions. The existing literature mostly focused on the impact of industrial transformation from the partial view. For example, Wang et al. (2019) showed the relationship between industrial structure and carbon efficiency of China, with results showing that resource-based regions should adjust industrial structure and explore ways to improve carbon efficiency. Zhu and Zhang (2021) studied the adjustment of the industrial structure across regions in the YRD, involving the industrial transfer between regions, and their results showed that inter-provincial industrial transfer in the YRD can promote emissions reduction. Chen et al. (2020) showed the effects of technological progress on carbon emissions of China's 30 provinces, and results found China's overall domestic technological progress reduced carbon emissions. Few studies combine them to perform a comprehensive analysis combining multiple factors (Cheng et al., 2018). In addition, the scale of most related studies is at the national (Dong et al., 2020) and sub-national level (Chen et al., 2020; Cheng et al., 2018; Zhu and Zhang, 2021), which cannot identify the heterogeneity of cities and make reasonable decisions about specific emission reduction plans for cities. Shan et al. (2018a) studied production-based carbon emission of 182 Chinese cities, decomposed into 17 different fossil fuels, 46 socioeconomic sectors, and seven industrial processes. Mi et al. (2016) calculated consumption-based carbon emissions for 13 Chinese cities at the city scale and found substantial differences between production- and consumption-based accounting in terms of both overall and per capita carbon emissions. The most developed cities (such as the YRD city cluster) in China are more likely to be categorised as consumption-based cities (Mi et al., 2016), thus, it will help them better take responsibility for climate change mitigation by calculating their carbon footprints (i.e. consumption-based emissions). Due to poor accessibility and timeliness of the city-level input-output (IO) table, data regarding city-level carbon flow in the YRD city cluster remains insufficient. Thus, comprehensive analysis of the impact of industrial transformation on carbon footprint in the YRD city cluster is missing.

In this study, we fill the knowledge gap of the impact of industrial transformation on the carbon footprint of cities in the YRD city cluster. We choose 2012-2015 as the study period, because China officially bid farewell to the development stage where the GDP growth rate exceeded 10% during this period, and the changes in the economic structure are becoming more and more obvious. Hence, we constructed an environmentally extended IO analysis model to account for the carbon footprint of 41 cities in the YRD city cluster and used structural decomposition analysis (SDA) to capture the driving factors of the change. The specific structure of this paper is as follows: in section 2, we briefly introduce research methods and data sources; and in section 3, we show the carbon footprint of 41 cities in the YRD city cluster from 2012 to 2015, the net carbon transfers between cities in the YRD city cluster, and the driving forces to carbon footprint change.

2. Methods

2.1. Environmentally extended multi-regional input-output analysis method

The IO analysis, developed by Leontief (1970), reveals the trade flow between different sectors through the supply chain. By extending the single region IO model to multi-regions, the multi-regional input-output model (MRIO) is the well-acknowledged tool employed to account for carbon footprint, which illustrates the inter-region and inter-industry relationships along supply chains and interregional trades. This method has been extensively used for environmental issues associated with economic activity, such as carbon emission (Meng et al., 2018; Zhang et al., 2020), air pollution (Ou et al., 2020), water sources (Zheng et al., 2019), energy consumption (He et al., 2019) and land use (Weinzettel et al., 2013). Although many efforts have been made to construct the MRIO table, they have mostly been at the national or subnational level, such as province or state (Huang et al., 2021; Zheng et al., 2020), but rarely at the city level because only a few cities publish their single region IO table, and detailed inter-city trade data are unavailable in most cases (Zheng et al., 2021). A MRIO table comprises a data set, as shown in table 1.

With the MRIO table, the equation can be expressed as:

$$\mathbf{X} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{F} \tag{1}$$

$$\mathbf{X} = \begin{bmatrix} x^1 \\ x^2 \\ \vdots \\ x^n \end{bmatrix}, \mathbf{A} = \begin{bmatrix} a^{11} & a^{21} & \cdots & a^{n1} \\ a^{21} & a^{21} & \cdots & a^{n2} \\ \vdots & \vdots & \ddots & \vdots \\ a^{n1} & a^{21} & \cdots & a^{nn} \end{bmatrix}, \mathbf{F} = \begin{bmatrix} f^{11} & f^{21} & \cdots & f^{n1} \\ f^{21} & f^{21} & \cdots & f^{n2} \\ \vdots & \vdots & \ddots & \vdots \\ f^{n1} & f^{21} & \cdots & f^{nn} \end{bmatrix}, \tag{2}$$

where $\mathbf{X} = (x_i^s)$ is the vector of total output and x_i^s is the total output of sector i in region s, $\mathbf{I}$ is the identity matrix and $(I - A)^{-1}$ is the Leontief inverse matrix. $\mathbf{A} = [a_{ij}^{rs}]$, and $a_{ij}^{rs} = z_{ij}^{rs}/x_j^s$ is the technical coefficient matrix of each sector from region r to region s; z_{ij}^{rs} is the intersectoral flows from sector i in region r to sector j in region s. $\mathbf{F} = (f_i^{rs})$ is the final demand matrix, and f_i^{rs} is the final demand from sector i in region r to region s.

The carbon footprint is calculated using an environmental extended multi-regional input-output analysis. On the basis of the carbon intensity per output $\mathbf{E}$ (that is, CO_2 emissions per unit of economic output), the carbon footprint is calculated:

$$\mathbf{C} = \mathbf{E}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{F} \tag{3}$$

where $\mathbf{C}$ is a vector of total CO_2 emissions in goods and services used for final demand; $\mathbf{E} = [e_i^r]$ is the matrix of carbon intensity per output; $e_i^r = \frac{CE_i^r}{x_i^r}$ represents carbon intensity per output of sector in i in region r; CE_i^r is CO_2 emission inventory from sector i in region r. In this study, carbon emissions driven by exports are not included because of the high uncertainty of nesting the city-level MRIO model into the global MRIO model, which accounts for 17% and 16.4% of production-based carbon emissions in 2012 and 2015, respectively.

2.2. CO₂ emission inventory construction

The fossil fuel-related CO_2 emission formula is as follows:

$$CE_{ij} = \sum_i \sum_j AD_{ij} \times NCV_i \times CC_i \times O_{ij} \tag{4}$$

where CE_{ij} is the CO_2 emissions caused by the sector j using the fossil fuel i; AD_{ij} is the consumption of fossil fuel i by sector j; NCV_i is the net calorific value of fossil fuel i; CC_i is carbon content of fossil fuel i; O_{ij} is oxygenation efficiency of fossil fuel i combusted in sector j.

The fossil process-related emissions refer to the emissions escaping from chemical reactions in the industrial processes.

$$CE_t = AD_t \times EF_t \tag{5}$$

where CE_t is the carbon dioxide emissions induced in the industrial processes t; AD_t is the production amount of processes t; EF_t is emission factor of processes t.

2.3. Structural decomposition analysis

Structural decomposition analysis (SDA) is a widely used approach to estimate the drivers of changes in carbon emissions and energy con-

Table 1

A diagram of the MRIO table

From/to			Intermediate Sectors						Final demand						Exports	Total output
			Region 1			...	Region s			Region 1			...	Region s			
			Sector 1	...	Sector j		Sector 1	...	Sector j	F1	...	F5		F1	...	F5	
Intermediate Sectors	Region 1	Sector 1	z_{ij}^{rs}							f_i^{rs}							e_i^r	x_i^r
		...															
		Sector i															
	...																
	Region r	Sector 1															
		...															
		Sector i															
Imports			im_j^s							im_j^s							
Value-added			va_j^s														
Total Input			x_j^s														

sumption (Meng et al., 2018; Mi et al., 2017). SDA applied to the city level is very rare. To our knowledge, there is only one previous study using SDA to extract the driving force and the study was just recently published. The study focused on the city level at the Jing-jin-ji region by Bai et al. (2021). Bai's study took the same approach like ours, based on the MRIO table constructed in the same methodology of constructing a city-level MRIO table. Previous research disassembled the drivers of carbon emissions into carbon emission per output (i.e. E in Eq. (1)), production structure, consumption structure, per capita consumption, population (Meng et al., 2018; Zheng et al., 2020). To estimate the industrial upgrade, E is further decomposed into carbon emission per GDP (K) and value-added rate (V), which is helped to measure the industrial upgrade. As our focus is the impact of industry evolution on carbon emission, we use the value-added rate ($V = [v_j^s]$) to represent ability to create value, and use Leontief inverse matrix (L) to represent production structure. $v_i^r = \frac{va_i^r}{x_i^r}$ is the value-added rate of sector i in region r; $va_i^r = x_j^s - z_j^s - import_j^s$ is value added of sector i in region r, that output minus intersectoral flows and exports. The final demand, i.e., F in Eq. (1), is further decomposed into consumption structure (S), consumption per capita (Q) and population (P). Thus, the changes in carbon footprint can be decomposed as:

$$\Delta C_Q = \frac{1}{2}(K_0 V_0 L_0 S_0 \Delta Q P_1 + K_1 V_1 L_1 S_1 \Delta Q P_0) \tag{11}$$

$$\Delta C_P = \frac{1}{2}(K_0 V_0 L_0 S_0 Q_0 \Delta P + K_1 V_1 L_1 S_1 Q_1 \Delta P) \tag{12}$$

where ΔC_K represents the impact of changes in carbon intensity per GDP; ΔC_V represents the impact of changes in value-added rate; ΔC_L represents the impact of changes in production structure; ΔC_S represents the impact of changes in consumption structure; ΔC_Q represents the impact of changes in consumption per capita; ΔC_P represents the impact of changes in population.

2.4. Data source

To trace the full supply chains of cities, we constructed a 68-region MRIO table with 42 sectors by the maximum-entropy approach, and the detailed method can be found in Zheng et al. (2021) . propose a feasible non-survey city-level MRIO construction framework without requiring official city-level SRIO tables. The proposed framework combines publicly available data and an entropy model to generate a supply-demand balance for cities and then links cities by the doubly

$$\Delta C = C_1 - C_0 = (\Delta K)VLSQP + K(\Delta V)LSQP + KV(\Delta L)SQP + KVL(\Delta S)QP + KVLS(\Delta Q)P + KVLSQ(\Delta P) \tag{6}$$

Where 0 refers to the year 2012, and 1 refers to the year 2015. Δ denotes the change in a factor. Each of the six factors in Eq. (6) represent the contributions to carbon emission changes induced by one force while other factors are kept constant. The six factors in our SDA model have 6! = 720 first-order decompositions, but this approach is too time-consuming for the modelling. Instead, we use the average of two polar decompositions (Dietzenbacher and Los, 1998). The influence of each factor can be respectively illustrated as:

$$\Delta C_K = \frac{1}{2}(\Delta K V_1 L_1 S_1 Q_1 P_1 + \Delta K V_0 L_0 S_0 Q_0 P_0) \tag{7}$$

$$\Delta C_V = \frac{1}{2}(K_0 \Delta V L_1 S_1 Q_1 P_1 + K_1 \Delta V L_0 S_0 Q_0 P_0) \tag{8}$$

$$\Delta C_L = \frac{1}{2}(K_0 V_0 \Delta L S_1 Q_1 P_1 + K_1 V_1 \Delta L S_0 Q_0 P_0) \tag{9}$$

$$\Delta C_S = \frac{1}{2}(K_0 V_0 L_0 \Delta S Q_1 P_1 + K_1 V_1 L_1 \Delta S Q_0 P_0) \tag{10}$$

constrained gravity model based on the principle of maximum entropy. The 68 regions include all 41 cities in the YRD city cluster, and 27 non-YRD provinces and municipalities of China, except for Hong Kong, Macao and Taiwan. Because the research scope is the carbon footprint of the YRD city cluster in China, the 27 non-YRD regions are also included in the table. The 42 sectors are shown in **Table S1**. Both MRIO tables of 2012 and 2015 are compiled using current year prices, and we chose 2012 as the price benchmark year and converted the price 2015 MRIO table into 2012 prices using deflators to eliminate the influence. We chose the agricultural producer price index to represent the deflator of agriculture sectors, chose the producer factory index to represent the deflator of industry sectors, and chose the household consumption index to represent the deflator of service sectors. We used the same deflator for the same sectors in the same provinces or municipalities. The deflator data were from the Province Yearbook. We utilized the CO_2 emission inventory for 41 cities and 27 province-level in 2012 and 2015 from the China Emission Accounts and Datasets (CEADs). The inventory covers 42 sectors, which is in line with the sector classification of the MRIO table.

Because of large heterogeneity between cities, we conducted a cluster analysis combined with the GDP share method of 41 cities in the YRD city cluster to summarize the characteristics. We used the proportion of GDP of different industries in 41 cities as indicators to conduct the cluster analysis to expose the cities' pillar industries. We used the K-means algorithm implemented using the Euclidean distance metric to group cities in this study. The detail method can be found in Shan et al. (2018a). The cluster analysis results show that group 1 included 13 cities with a higher ranking in the light manufactory, group 2 included nine cities with a higher ranking in the heavy manufactory, group 3 included eight cities with high ranking in high-tech manufactory and group 4 included 11 cities with high-ranking in service (Fig. 1S a, b). Therefore, we named group 1, group 2, group 3 and group 4 as light industry cities, heavy industry cities, high-tech cities and service-based cities (Table S2). Some cities have the same English names, so the abbreviation of the province where they are located is added after them. JS stands for Jiangsu, ZJ stands for Zhejiang, and AH stands for Anhui. There are statistically significant differences in per capita GDP among the four groups of city types (p<0.001): high-tech cities are the highest, followed by service-industry cities, followed by heavy-industry cities, and light-industry cities with the lowest industrial cities (Fig. 1S c).

3. Results

3.1. Carbon footprint in the Yangtze River Delta from 2012 to 2015

From 2012 to 2015, the carbon footprint of the YRD city cluster increased from 1178.4 Mt to 1298.9 Mt with their share in total national footprint rising from 14.8% to 16.6%. The sum of the carbon footprints of the top 10 cities accounted for 61.2% of the carbon footprint of the YRD city cluster in 2012 and 61.6% in 2015 (Fig. 1). The top 10 cities were developed cities, including six megacities in the YRD cities cluster, such as Shanghai (municipality), Nanjing (provincial capital), Hangzhou (provincial capital), Hefei (provincial capital), Suzhou (JS) (economically developed city) and Ningbo (economically developed city), which were concentrated on the coastal and the central part of the YRD city cluster. The carbon footprint of 73.2% of cities (30 cities) in the YRD city cluster had increased from 2012 to 2015. 91% of the service-based city had an increase in their carbon footprint, which contributed to 82.5% of the growth in carbon footprint. Among them, the carbon footprint of Shanghai had the largest increase by 42.2 Mt, and per capita consumption in Shanghai has further improved by 37.8%. Half of the heavy industry cities showed a decrease in carbon footprint, among which the
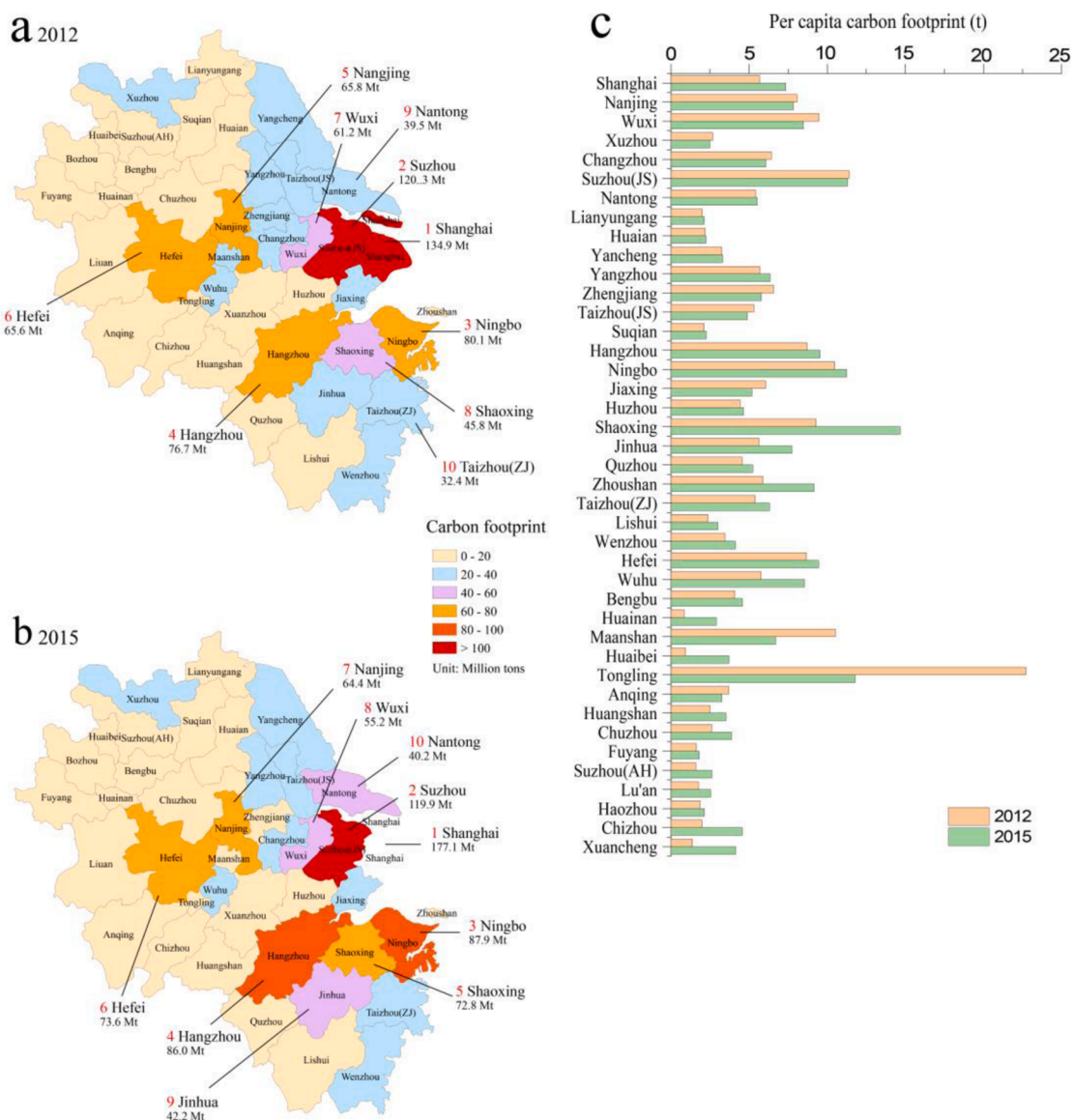

Fig. 1. The carbon footprint of 41 cities in Yangtze River Delta from 2012 (a) to 2015 (b), and per capita carbon footprint (c) during the same period.
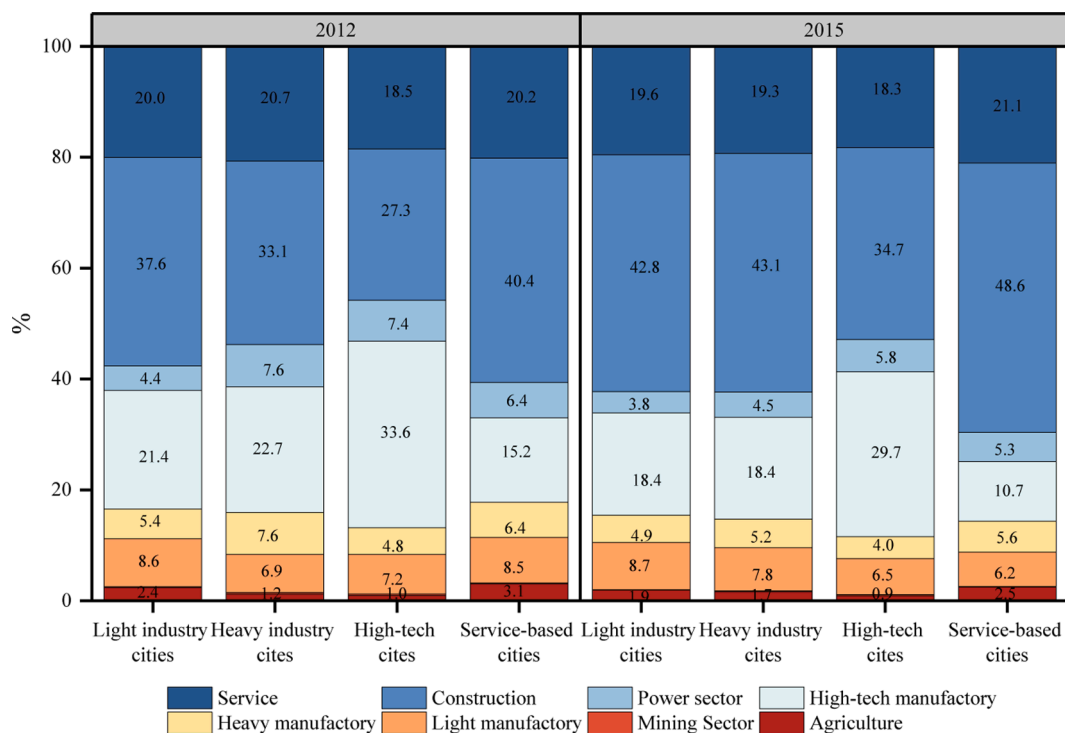
Fig. 2. The proportion of carbon footprint of seven aggregated sectors in four types of cities (Because carbon footprint of the mining sectors is too low, the proportion is not marked).

carbon footprint of Tongling fell most, decreasing by 8.0 Mt because of the elimination of backward production capacity in the new normal era.

Per capita carbon footprint is relatively high in economically developed cities, but some small cities are exceptions (Fig. 2). Take 2015 as an example, per capita carbon footprint of six megacities was 9.0 t, 49.8% higher than the YRD city cluster average (6.0 t per capita), however, relatively less developed cities such as Maanshan (6.7 t per capita) and Tongling (11.8 t per capita) still have high per capita carbon emissions. The megacities are economically developed and have high per capita consumption, so does per capita carbon footprint; Maanshan and Tongling are cities with rich mining resources, so the heavy industry in these cities accounts for more than 40% of GDP, and they have a high carbon intensity of 0.06 Mt/Billion RMB and 0.12 Mt/Billion RMB, respectively (more than the YRD city cluster average carbon intensity of 0.03 Mt/Billion RMB). In the new normal era, the per capita carbon footprint of Huaibei, Huainan and Xuancheng, small cities dominated by heavy industry, more than doubled, increasing by 295.9%, 246.5%, and 202.6%, respectively, because of surging per capita consumption which increased 171.7%, 333.8% and 216.5%. The per capita carbon footprint of Tongling, Maanshan decreased significantly, by 47.7% and 37.3%.

From a sectoral perspective, the carbon footprint is mainly concentrated in the following industries: construction, service and high-tech manufactory, and the total accounted for 77.4% in 2012 and 81.0% in 2015 (Fig. 2). To extract the characteristics of the city, we divided 41 cities into four types according to their industrial structure to discuss the driving factors. Service-based cities had the highest proportion of carbon footprint in service (20.2% in 2012 and 21.1% in 2015) and construction (40.4% in 2012 and 48.6% in 2015). High-tech cities had the highest proportion of carbon footprint in high manufactories (33.6% in 2012 and 29.7% in 2015). The proportion of carbon footprint in the construction sector of the YRD city cluster had increased the most, from 35.6% in 2012 to 43.7% in 2015, and of which heavy industry cities have risen the most, with an increase from 33.1% in 2012 to 43.1% in 2015. The proportion of carbon footprint in the service sector of the YRD city cluster had increased slightly, from 19.7% in 2012 to 20.0% in 2015, and of which only service-based cities increased slightly, from

20.2% in 2012 to 21.1% in 2015. The proportion of high-tech manufactories of the YRD city cluster decreased from 22.0% in 2012 to 17.3% in 2015, and high-tech cities have the smallest decline. For other high carbon intensity sectors, such as the mining sector, power sector and heavy manufactory, the proportion of these sectors of the YRD city cluster decreased from 8.3% in 2012 to 7.1% in 2015, and their proportion declined in all four types of cities and declined most in heavy industry cities.

3.2. Carbon emissions embodied in inter-city supply chain

Because of the economic integration in YRD, YRD cities are increasingly more connected by trade. Trade-related embodied carbon emission within the YRD city cluster rose from 384.2 Mt in 2012 to 417.4 Mt in 2015, accounting for 32.6% of carbon footprint in the YRD city cluster in 2012 and 31.4% in 2015, respectively. Trade-related embodied carbon supplied by the top 10 carbon footprint cities (Fig. 1) was 46.5%, but they consumed 56.8% in 2012; however, trade-embodied carbon supplied by the top 10 carbon footprint cities decreased rapidly to 37.3%, and what was consumed by them decreased slightly to 54.2% in 2015 (Fig. 3). The economic advance causing higher costs of production (e.g. high land rent and labour cost) in these megacities encouraged the transfer of carbon-intensive industries to other areas, resulting in a rapid reduction in their production-based emissions (Zhao et al., 2020). However, the decline in the proportion of trade embodied carbon supplied by core cities (9.2%) is much greater than the decline in the proportion of trade embodied carbon consumed by them (3.1%), indicating that the consumption scale of megacities is expanding. It is worth noting that the trade-related embodied carbon emission supplied of service-based cities and high-tech cities exceeds consumed, while supplied of light-industrial cities and heavy-industry cities are smaller than consumed (Fig. 3). Although goods and services need to be traded between different cities, the carbon intensity in light-industrial cities and heavy-industrial cities is higher, and heavy-industrial cities and light-industrial cities are often cantered on key cities (usually are service-based cities) near them, often taking over
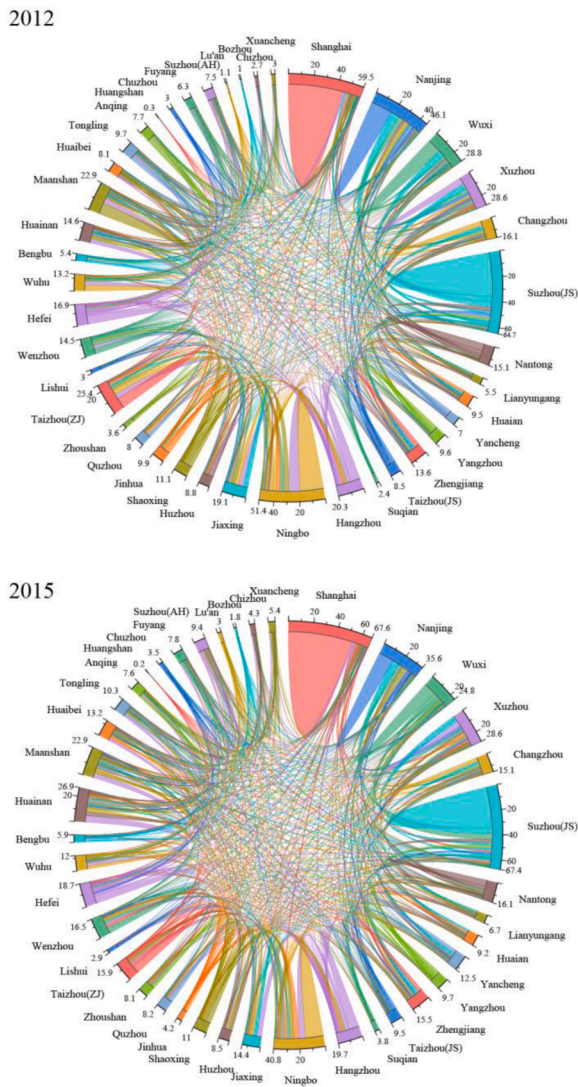
Fig. 3. Carbon flows between 41 cities in the YRD city cluster in 2012 and 2015.

the core city's backward production capacity.

The YRD promotes the integrated development of regions and builds the integrated development of metropolitan areas, such as the Hangzhou metropolitan area, the Hefei metropolitan area, and the Suzhou-Wuxi-Changzhou metropolitan area. The formation of these metropolitan circles has intensified the communication between the core cities of the metropolitan circle and surrounding cities and promoted the formation of the pattern of net carbon flow (carbon inflow – carbon outflow) (Fig. 4). The pattern of northern of the YRD city cluster (Jiangsu) is that Xuzhou flowed trade embodied carbon to Suzhou (JS) and its nearby cities, and the trend intensified from 2012 to 2015. The pattern of the central inland area of the YRD city cluster (Anhui) is that high carbon intensity cities around Hefei (such as Huainan, Maanshan, Huaibei and Wuhu) flow trade embodied carbon into Hefei, and the trend intensified from 2012 to 2015. The pattern of south YRD (Zhejiang) is that eastern coastal cities, such as Ningbo and Taizhou (ZJ), flowed trade embodied carbon to central regions, such as Hangzhou and Shaoxing, and the carbon flow between cities is not as strong as that of other provinces because the light industry has a relatively large proportion in the cities of Zhejiang, and different cities have different pillar industries, and most of the products produced are used for export.
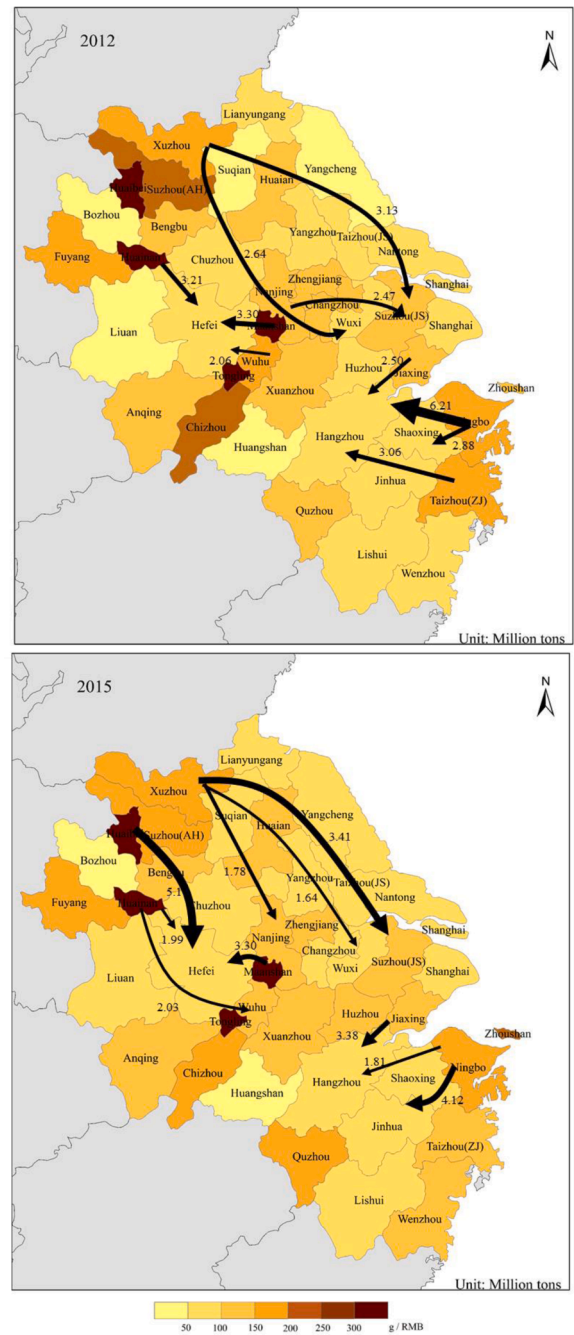

Fig. 4. Net carbon flow within the YRD city cluster and carbon intensity per output of cities in the YRD city cluster in 2012 (a) and 2015 (b). The figure shows the largest 10 carbon flows.

3.3. Driving factors of change in carbon footprint

The change in carbon footprint is affected by many socioeconomic drivers (Fig. 5). These drivers include carbon intensity per GDP, value-added rate, production structure, consumption structure, per capita consumption, and population. The YRD city cluster is one of the regions with the most dynamic economy, the highest degree of openness, and the strongest innovation capability in China. The population of the YRD city cluster increased by 1% from 2012 to 2015, and responsible for the growth of carbon emissions by 15.3 Mt. There are several plans issued by the central government to put forward the strategic position of the YRD, for example, the "YRD Regional Planning" was issued in 2010, the "YRD City Cluster Development Plan" was issued in 2016, and the "YRD
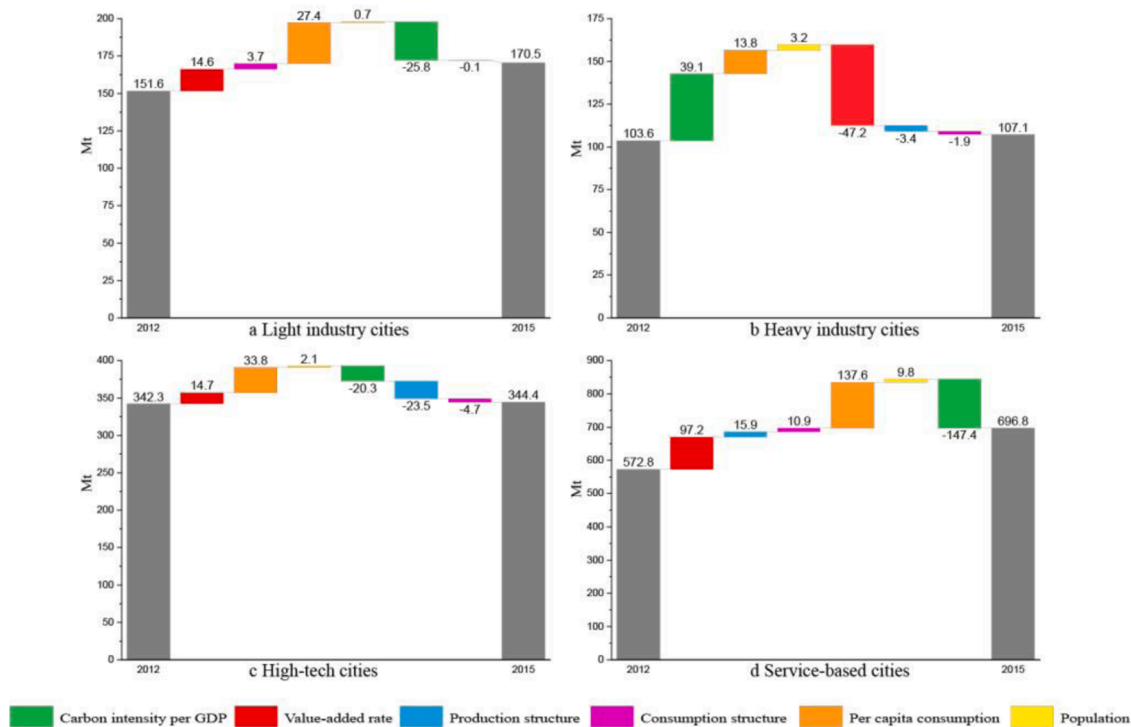
Fig. 5. The contribution of different driving factors to the changes in carbon emissions of the four city types including light industry cities (a), heavy industry cities (b), high-tech cities (c) and service-based cities (d).

Regional Integrated Development Plan" was issued in 2019. With its socioeconomic advantage, people in YRD are getting richer with higher purchase power, and per capita consumption increased from 45.3×10^3 RMB in 2012 to 53.5×10^3 RMB in 2015, which exceeds the China average of 12% in 2012 and increased to 16.5% in 2015. Per capita consumption is a major driving force to increase carbon emission by 212.7 Mt. Per capita consumption in the YRD city cluster has increased by 17% from 2012 to 2015. The per capita consumption of service-based cities increased the most among four types of cities, by 24.5%, and they were affected by this factor to promote the increase in carbon emissions by 137.6 Mt. Consumption structure change has promoted the increase of carbon emissions by 7.9 Mt in cities in the YRD city cluster. The share of the service industry and construction industry in the consumption structure of the YRD city cluster has increased, from 22.6% and 39.8% in 2012 to 28.0% and 40.9% in 2015. In addition, the proportion of consumption from other regions increased from 9.5% in 2012 to 10.5%.

The industrial transformation includes production structure changes and industrial transfer. Production structure change promoted a slight decrease of carbon emissions by 11.1 Mt in the YRD city cluster, which showed that the YRD city cluster's production technology is even lower carbon. The changes in production structure have promoted the increase in carbon emissions of service-based cities and the decrease in carbon emissions of other types of cities. Decomposing the contribution of changes in the production structure to different regions, we found that the existence of industrial transfer has made local production cleaner in the YRD city cluster, but production along the industrial chain more carbon-intensive (Fig. 6a). For service-based cities, their domestic production structure changes have promoted carbon emission reduction in service-based cities (–40.5 Mt), but changes in the production structure of non-YRD regions have contributed to the increase in carbon emissions in the service-based city (+56.4 Mt). For example, Shanghai is a typical service-based city, and domestic production structure changes have promoted its carbon emission reduction (–8.1 Mt), which was lower than the increase in carbon emissions (+9.1 Mt) caused by changes in the production structure in other regions, indicating that service-based cities have imported higher-carbon products from these regions. For light

industrial cities, only changes in the domestic industrial structure play a role in reducing emissions (–5.3 Mt); but for heavy industrial cities, changes in the domestic (–5.1 Mt) and central (–0.6 Mt) industrial structure play a role in reducing emissions. For high-tech cities, domestic (–27.8 Mt), central (–1.5 Mt) and northern (–0.6 Mt) industrial structure changes have played a role in reducing emissions. During the industrial transformation, their domestic production structure is more low-carbon in the YRD city cluster, but backward high-carbon industry industries, especially in service cities, tended to be transferred to other regions.

Carbon intensity is often measured by emission per output (i.e. the ratio of CO_2 to output) (Meng et al., 2018; Zheng et al., 2019), indicating CO_2 emitted per unit value of production. The intensity per output decreased in the YRD city cluster from 36 g/RMB in 2012 to 30 g/RMB in 2015, causing carbon emission increase by 75.0 Mt (Fig. 5. the sum of the contribution of carbon emission per GDP and value-added rate). However, the value-added rate was separated in this study to judge the industrial upgrade, so we use the emission per GDP (i.e. the ratio of CO_2 to GDP), indicating CO_2 emitted per profit. Carbon emission per GDP decreased from 115 g/RMB in 2012 to 112 g/RMB in 2015, but promoted carbon emission increasing by 79.3 Mt in the YRD city cluster (Fig. 5). It is noted that carbon intensity per GDP of service-sector cities fell by 6.7% (from 102.7 g/RMB to 95.6 g/RMB) have increased carbon emissions by 97.2 Mt. This may be due to the increasing carbon intensity of industries. For example, carbon intensity in Shanghai and Hangzhou have decreased 7.7% and 3.0% from 2012 to 2015 respectively, but the intensity of their electrical sector has increased by 142.0% and 83.1% respectively. All industries use electricity directly or indirectly, therefore a change of intensity in Shanghai and Hangzhou caused emission increase by 23.1 Mt and 16.8 Mt.

Industrial transformation in the YRD expands the scale of the high-tech manufacturing industry. However, due to China's position in the middle of the global industrial chain at this stage, the large-scale manufacturing industries in YRD are about the process of processing and assembly. For example, China's electronic equipment manufacturing industries are highly reliant on products and services
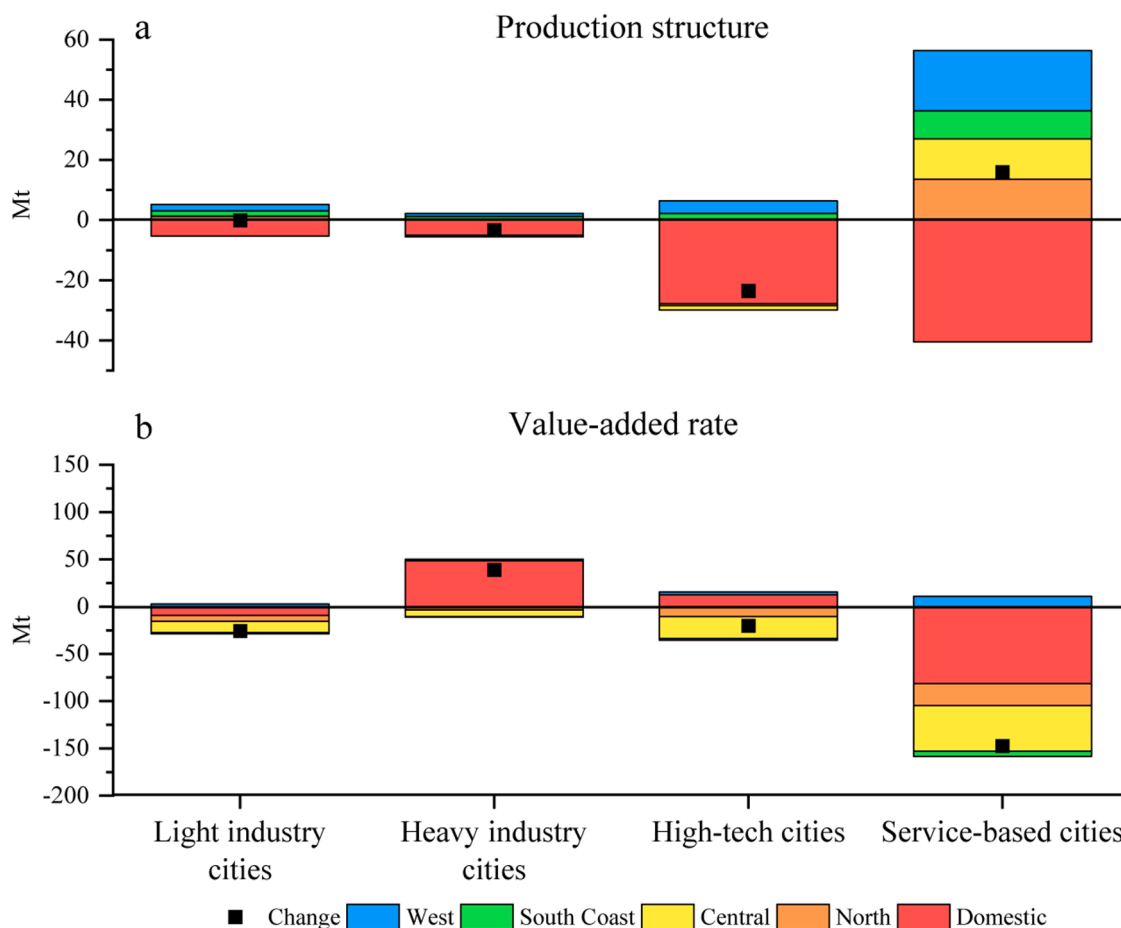
Fig. 6. . (a) Production structure (b) and value-added rate from different regions contributed to carbon emission change in four types of cities in the YRD city cluster from 2012 to 2015. The colour bars represent different regions, and the black point represents emission change.

from other countries. The industry often saw high profits of core technologies and core components are owned by foreign companies, which lock the industry in the low position of the global value chain. The value-added rate of the industry is 8.8% lower than others. The decline in the value-added rate decreased from 0.31 to 0.27 in the YRD city cluster, indicating that the industry is degraded in terms of profit, leading to a decrease in carbon emissions by 154.2 Mt from 2012 to 2015 (Fig. 5). Elimination of backward production capacity will affect economic development in the short term, even though the goal of environmental protection was achieved. However, domestic-led changes in the value-added rate have promoted the increase in carbon emissions in some cities, which were mainly heavy industry cities and some high-tech cities (Fig. 6b). The value-added rate of these cities has also decreased. For example, Xuzhou as a heavy industry city saw its value-added rate decline by 0.3% from 2012 to 2015, but its carbon emission increased. The reason behind the decrease in the value-added rate may promote the increase in carbon emissions in these cities is that the products produced in these cities are more consumed as intermediate products produced by industries in other cities. China's output was growing faster than GDP from 2012 to 2015 and the value-added rate has fallen by 8.3%, affected by the global economic recession in 2015, indicating that the carbon emissions from the production of intermediate products will increase (Ou et al., 2019).

4. Discussion and Conclusion

Our study revealed the carbon footprint of the YRD city cluster increased more than the China average, and the top 10 carbon footprint cities - including all megacities in the YRD city cluster - accounted for

61.2% in 2012 to 61.6% in 2015 of the YRD city cluster, indicating the high concentration of carbon footprint in YRD city cluster. That highlights the higher responsibility of the megacities in the developed regions. Construction, service and high-tech manufactory industries are the big contributors and the share is increasing from 2012 to 2015. The megacities are the pioneers in the industrial transformation of the YRD city cluster, they tend to transfer more high-carbon industries to other regions and purchase carbon from other regions to take the lead in achieving emission reduction targets. Therefore, small cities become the successor to take over the megacities' backward production capacity and increase in carbon emission.

Among the six socioeconomic drivers decomposed by SDA, the decrease in value-added rate and change in production structure caused a reduction in carbon emissions in the YRD city cluster from 2012 to 2015, and remain four drivers (i.e. carbon emission per GDP, consumption structure, per capita consumption and population) causing increases in carbon emission in the YRD city cluster. Although the whole carbon intensity in YRD declined on the production side, it increased carbon emission due to an increase in carbon intensity in key industries leading to an increase in overall consumption-based carbon emissions. The decline in emissions caused by changes in the value-added rate and production structure was the result of sustainable strategies and low-carbon policies when the industrial transformation occurred in the new normal era. The government has devoted more effort to improving energy efficiency; one example is the elimination of backward and outdated production capacity in energy-intensive industries, and the production structure of local industries in the YRD city cluster is shifting towards a lower carbon and green direction. This is due to the progress of production technology in the YRD city cluster, which also reduces the

carbon emissions per output in the YRD city cluster (Fig. 3). Because of the powerful control measures in environmental protection during the new normal era, a decline in the value-added rate from 2012 to 2015, shows that industrial transformation has a painful period, and environmental protection has affected economic development in the short term. Although the industry in the YRD city cluster has undergone a transformation, it cannot be determined that its industrial upgrading will have been completely successful from 2012 to 2015, because the quality of its economy was affected.

Nevertheless, we must be aware of the YRD city cluster importing high-carbon products from other regions, resulting in a "carbon leakage" phenomenon that transfers local carbon emissions to other regions. Carbon leakage is originally caused by trade, especially international trade. Developed and developing countries attach different importance to the environment, so it is easy to transfer pollutant emissions through international trade. Lin et al. (2014) found that a large fraction of Chinese emissions is due to the manufacture of goods for foreign consumption and about 21% of export-related Chinese emissions were attributed to China-to-US export. When some developing countries develop their economic strength, this phenomenon exists in them and less developed areas. Meng et al. (2018) found that when trade among developing nations has more than doubled between 2004 and 2011, some production activities are relocating from China and India to other developing countries after China, and the emissions embodied in exports from less-developed regions such as Vietnam and Bangladesh have surged. Our study revealed that even in a country, measures to control carbon emissions in developed regions may still cause carbon leakage. We need to be vigilant against this phenomenon because there is no tariff in intra-country trade, which is more likely to cause unfairness in the responsibility of reducing emissions between regions.

There are some uncertainties in our study: (1) Due to the lack of observed intercity trade data, the parameters used in the gravity model are estimated by the provincial trade flow to the surrounding province with the assumption of an identical trade pattern between intercity and interprovince. This may be less accurate because regional heterogeneity exists at the city level. (2) Different cities have different levels of inflation from 2012 to 2015. Using the same deflator in the same province will cause errors. (3) There are two uncertainties in the carbon emission inventory, one is the uncertainty of the emission factor, the emission factors of China's fossil fuel combustions may have large variations as discussed in subsequent studies (Shan et al., 2018b); and the other is the uncertainty of the energy use data, and because the statistical calibration of energy consumption in China is not completely consistent, and there is a between the sum of the urban energy consumption statistics and the sum of the provincial energy consumption statistics (Guan et al., 2012).

Based on our results, several policy suggestions were made for policymakers. As the YRD city cluster economy will continue to maintain a growth rate, industrial transformation is required to reduce carbon emissions by developing a low-carbon economy and innovating low-carbon technologies, rather than affecting economic development. Megacities have more low-carbon technologies, which need to be shared with small cities to work together to reduce emissions. Several policies need to be proposed to deal with carbon leakage. The first is to strengthen the role of the carbon market and incorporate more companies and industries into the trading system. In such schemes, firms receive emission permits in proportion to their output, and they have an incentive to employ carbon-reduction technologies that would yield the same amount of output with fewer emissions, and therefore lead to emission permits surplus, and extra revenues can be generated by selling the excess permits to other firms in the market for emission allowances. The second is to levy taxes on imported goods with a high proportion of carbon emissions. It can be used to punish free-riders for their lack of ambitious climate policies, and companies that want to import high-carbon emissions instead of local high-carbon emissions (Jakob, 2021). The third is to take the lead in focusing on key industries in the

supply chain that supplies more to other industries to save energy and reduce carbon.

Credit Author Statement

C.X. and H.Z. designed the research. C.X. led the study and drafted the manuscript with efforts from all other authors (H.Z., J.M., S.L., P.D., and Y.S). H.Z. C.X. and S.L collected raw expenditure data. C.X. and H.Z. conducted decomposition analysis.

Declaration of Competing Interest

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

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