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Spatial-temporal Heterogeneity of Industrial Structure Transformation and Carbon Emission Effects in Xuzhou Metropolitan Area

QIU Fangdao[1], YUAN He[1], BAI Liangyu[1], LI Fei[2]

(1. *School of Geography*, *Geomatics and Planning*, *Jiangsu Normal University*, *Xuzhou* 221116, *China*; 2. *Party school of the Liaoning Provincial Committee of Chinese Communist Party*, *Shenyang* 110004, *China*)

Abstract: Employing decoupling index and industrial structure characteristic bias index methods, this study analyzed the spatial-temporal characteristics of industrial structure transformations and their resulting carbon emissions in the Xuzhou Metropolitan Area from 2000 to 2014, with a focus on their relationships and driving factors. Our research indicates that carbon emission intensity from industrial structures in the Xuzhou Metropolitan Area at first showed an increasing trend, which then decreased. Furthermore, the relationship between emissions and industrial economic growth has been trending toward absolute decoupling. From the perspective of the center-periphery, the Xuzhou Metropolitan Area formed a concentric pattern, where both progress towards low emissions and the level of technological advancement gradually diminished from the center to the periphery. In terms of variation across provinces, the ISCB index in the eastern Henan has decreased the slowest, followed by the southern Shandong and the northern Anhui, with the northern Jiangsu ranking last. During this period, resource- and labor- intensive industries were the primary growth industries in the northern Anhui and the eastern Henan, while labor-intensive industries dominated the southern Shandong and capital-intensive industries dominated the northern Jiangsu. In terms of city types, the spatial pattern for industrial structure indicates that recession resource-based cities had higher carbon emission intensities than mature resource-based cities, followed by non-resource-based cities and regenerative resource-based cities. Generally, the industrial structure in the Xuzhou Metropolitan Area has transformed from being resource-intensive to capital-intensive, and has been trending toward technology-intensive as resource availability has been exploited to exhaustion and then been regenerated. Industrial structure has been the leading factor causing heterogeneity of carbon emission intensities between metropolitan cities. Therefore, the key to optimizing the industrial structure and layout of metropolitan areas is to promote industrial structure transformation and improve the system controlling collaborative industrial development between cities.

Keywords: industrial structure transformation; industrial structure characteristic bias; carbon emission effect; spatial-temporal pattern; Xuzhou Metropolitan Area

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1 Introduction

Eco-friendly development is a major concept directing socio-economic development during the 13th Five-Year Period, yet the current conflict between environmental protection and economic growth is a barrier to implementation. The key to addressing this problem lies in an industrial system that enables low-carbon-cycle development, which is based on industrial low-carbon transformation (Huang and Li, 2015). Metropolitan areas, especially those with rapid economic growth, industrial structure transformations, and shifts in spatial structures, are driving high-speed industrial growth and industrial agglomeration; however, they are also the

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Corresponding author: Qiu Fangdao. E-mail: qiufangdao@163.com

largest contributors to environmental pollution, especially carbon emissions. Therefore, achieving low-carbon eco-friendly development through industrial structure transformation has become a popular topic among scholars (Barassi *et al*., 2011; Liang *et al*., 2016; Yuan *et al*., 2016; Xia *et al*., 2017). Research conducted domestically and internationally on the relationships between industrial structure and carbon emissions has primarily focused on four aspects: employing decomposition models, such as the Log-Mean Divisia Index (LMDI) and Laspeyres index, to decompose regional carbon emissions, carbon emission intensity, and their factors, to comprehensively analyze the impact of industrial structure transformation on carbon emissions and their intensity (Ang, 2005; Liu *et al*., 2007; Sun *et al*., 2010; Shi and Li, 2011; Lv *et al*., 2012b; Xu and Ang, 2013; Cansino *et al*., 2016). Liu *et al*. (2016) applied a geographically and temporally weighted regression model to investigate driving factors on industrial carbon emissions in China, and indicated that population, affluence, and technology have a significant impact on industrial carbon emissions, while energy intensity, energy prices, and opening to the outside world were insignificant factors. Wang and Yang (2015) analyzed the factors that influence the relationship between industrial growth and environmental pressure in the Beijing-Tianjin-Hebei (BTH) economic circle from 1996 to 2010. Their results indicated that rapid economic growth was one of the main factors hindering industrial decoupling, and that energy structure and the energy intensity of the industrial decoupling process had an important contribution.

Exploring the impacts of spatial-temporal pattern and regional differences in industrial structures on carbon emission, based on methods such as GIS spatial analysis and regression models (Debabrata *et al*., 2001; He *et al*., 2011; Fang and Sun, 2013; Padilla and Duro, 2013; Wang and Zhao, 2015; Wang and Zhao, 2016). Sun *et al.* (2016) studied the spatial characteristics and economic spillover effect of inter-provincial carbon emission transfers. They found that carbon emissions in most provinces were comparatively large and the overall carbon emissions import was higher than exports. Furthermore, the economic spillover effects of the carbon emission import are greater than that of the export. Moran's *I* index was used to reveal the spatial agglomeration characteristics of provincial carbon emission transfer in China. Xu *et al.* (2017) used a gravity model to study the temporal and spatial changes in industrial carbon transfers in the process of industrial transformations in China. Liu (2015) established a multi-regional input-output model to assess regional differences in carbon emissions and inter-regional carbon flows, and identified that the northeastern and northwestern regions in China would take on much greater carbon emission responsibilities under the production-based principle. In accordance with these consumption-based principles, the eastern and southern coastal regions would need to take on much greater carbon emission responsibilities.

Using the decoupling index and Granger test of causality, some researchers explore the relationships between economic growth and carbon emissions, and then reveal the interactions between industrial structure and carbon emissions (de Freitas and Kaneko, 2011; Yao and Yu, 2012; Gai *et al*., 2014; Zhu *et al*., 2014; Wang *et al*., 2015). Wang and Yang (2015) studied the relationships between industrial economic growth and carbon emissions in the BTH economic corridor, and pointed out that the relationship between industrial economic growth and carbon emissions mainly showed weak decoupling' during the Ninth Five-Year Plan period (1996–2000) and Eleventh Five-Year Plan period (2006–2010), and 'weak coupling' during the Tenth Five-Year Plan period (2001–2005).

Differentiating carbon emission types across different industries based on the distribution of carbon emissions and their intensity to discuss industry heterogeneity in carbon emissions (Lv *et al*., 2012a; Jia and Zhang, 2012; Wang *et al*., 2012). These studies have mostly been conducted at the national provincial, or city level, with few at the metropolitan level.

This study used the Xuzhou Metropolitan Area as an example to construct an industrial structure characteristic bias index (ISCB). Use of this analysis, and from the perspective of space-time coupling, elucidates the characteristics of industrial structure transformation and carbon emissions in growing metropolitan areas, and their decoupling relationships. This study then further explores the influencing mechanisms on industrial carbon emissions in growing metropolitan areas. This research should be a helpful reference for industrial restructuring and industrial layout optimization in growing metropolitan areas, which can assist in achieving industrial green transformation.

2 Materials and Methods

2.1 Study area

At the borders of Jiangsu, Shandong, Henan, and Anhui provinces, the Xuzhou Metropolitan Area is ranked high in *National Main Functional Area Planning*, with eight cities covered in this area: Xuzhou, Lianyungang, and Suqian in Jiangsu Province, Zaozhuang and Jining in Shandong Province, Suzhou and Huaibei in Anhui Province, and Shangqiu in Henan Province. All eight, except Lianyungang and Shangqiu, are resource-based cities as defined by the *Sustainable Development Plan of Resource-dependent Cities Nationwide (2013–2020)* (Fig. 1). In 2014, Xuzhou Metropolitan Area covered a landmass of 6 6540 km^2, accommodated a population of 5115.26 × 10^4, and had a GDP of 18 211.82 × 10^8 yuan, respectively accounting for 0.69%, 3.74%, and 2.83% of the Chinese totals. The output ratio for the first, second and third industry in Xuzhou Metropolitan Area was 12.54: 48.40: 39.06, and the industrial gross domestic product reached 7.59 × 10^{11} yuan, 41.60% of the area total. The industrial energy consumption intensity reached 3.29 t/10^4 yuan, 1.81 times and 3.85 times, respectively, of the values nationally and for the province of Jiangsu (Jiangsu Provincial Bureau of Statistics, 2005–2015; Shandong Provincial Bureau of Statistics, 2005–2015; Henan Provincial Bureau of Statistics, 2005–2015; Anhui Provincial Bureau of Statistics, 2005–2015). In recent years, resource-based industries in the Xuzhou Metropolitan Area have had gradually diminishing roles in fueling economic growth, as primary resources, such as coal, have decreased and problem issues, such as the deleterious effects of pollution, have grown. This dichotomy has led to an increasingly fragile industrial system, escalating the conflict between the industrial structure and the environment. Therefore, exploring the coupling relationship between industrial structure and carbon emissions in this area, and characterizing its driving forces, should provide the foundation for reconfiguring its industrial structure and layout pattern to achieve coordination between the economy and the environment. At the same time, this information will provide a blueprint for other similar metropolitan areas engaged in optimizing their industrial structure and layout pattern for eco-friendly development.

2.2 Research methods and data collection

2.2.1 Decoupling Model

The decoupling model employed here was initiated by OECD (the Organization for Economic Co-operation and Development) to guide agricultural policymaking. It was first introduced into the field of environment and resources by the World Bank in the 1990s to analyze the impact of economic activity on the environment (de Bruyn and Opschoor, 1997). Decoupling refers to the situation in which the rate of growth in the consumption of resources and environment in a certain area within a certain time period is less than the economic growth

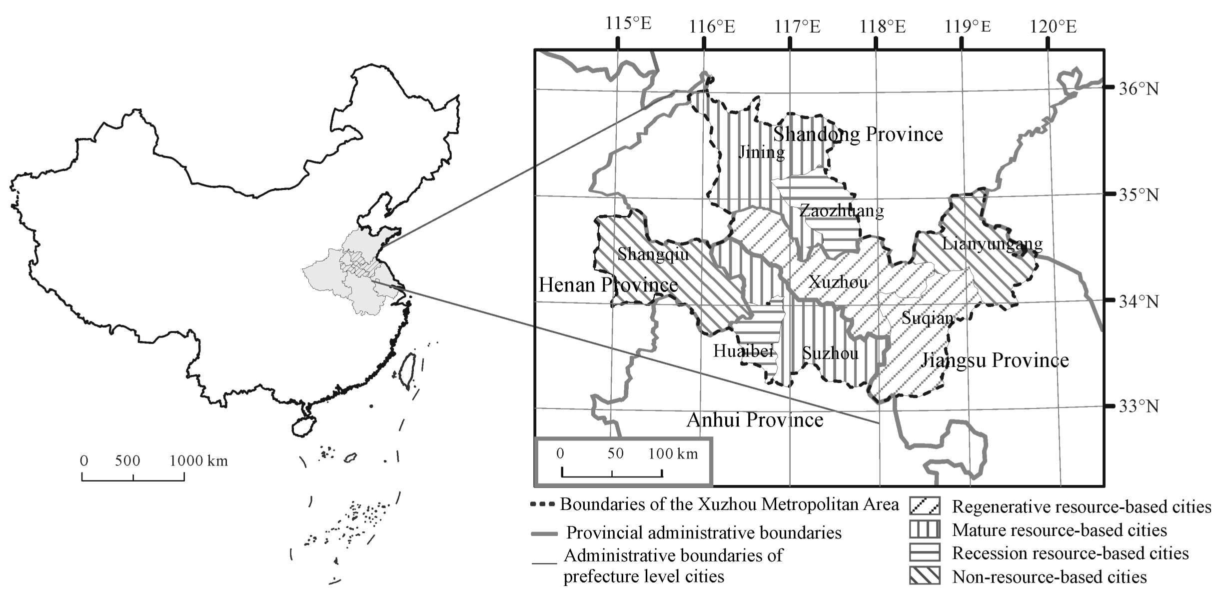

Fig. 1 Location and city types of Xuzhou Metropolitan Area

rate. It can be further divided into absolute decoupling and relative decoupling. Absolute decoupling occurs when the rate of consumption of resources and environment remains at the same level, or even declines, during economic-scale expansion; relative decoupling occurs when the rate of growth of consumption of resources and environment lags behind the expansion rate at the economic scale (de Bruyn and Opschoor, 1997; Zhao *et al*., 2011). This study employs the decoupling elasticity index to analyze the evolving relationship between industrial progress and carbon emissions from 2000 to 2014. The index is calculated as follows:

$$DS_i = \frac{\Delta C}{\Delta IG} = \frac{(C_t - C_0)/C_0}{(IG_t - IG_0)/IG_0} \tag{1}$$

where DS_i refers to the decoupling index of the relationship between a certain carbon emission index and industrial GDP during period i; ΔC is the growth rate of industrial carbon emission volume, which shows the pressure on the environment; C_0 and C_t are respectively the emissions of the base year and last year within period i; ΔIG is the growth rate of regional gross industrial output, reflecting the state of industrial driving forces; IG_0 and IG_t are respectively the output of the base year and last year within period i. Given the economic reality of all cities within the Xuzhou Metropolitan Area since 2000, negative ΔIG were removed in this study. Based on references to similar research findings (Zhao *et al.,* 2011; Wang *et al*., 2014), the degree of decoupling was classified into one of the four categories in Table 1.

Table 1 Classification criteria for the degree of decoupling between carbon emissions and industrial development

Decoupling degree		ΔIG	ΔC	$\Delta C/\Delta IG$	Implication
Absolute decoupling		>0	<0	<0	Industry growing rapidly while carbon emissions decline
Relative decoupling	I	>0	>0	(0, 0.5)	Industrial growth rate higher than the growth rate of carbon emissions
	II	>0	>0	[0.5, 1)	
Critical state		>0	>0	=1	Industrial growth rate equal to the growth rate of carbon emissions
Coupling state		>0	>0	>1	Industrial growth rate lower than the growth rate of carbon emissions

2.2.2 *Industrial structure characteristic bias*

Industrial structure controls the regional environment and resources, and it varies spatially and temporally, which results in correspondingly different impacts. To better reveal the spatial characteristics of industrial structure transformation in the Xuzhou Metropolitan Area, this study generates an Industry Structure Characteristic Bias (ISCB) from the perspective of carbon emissions. Then, the relationships between carbon emission characteristics and the industrial structures in cities in the Xuzhou Metropolitan Area are discussed. The ISCB is calculated as follows (Midelfart-Knarvik *et al.*, 2000; Wang *et al*., 2014):

$$ISCB_i = \sum_{k=1}^{j} S_i^k \cdot CI_k \tag{2}$$

where $ISCB_i$ refers to the industrial structure characteristic bias of city i; S_i^k is the ratio of the output in sector k to the Gross Industrial Output in city i; CI_k is the carbon emission index per unit of output in sector k; in this study, 10 000 yuan worth of industrial yield is one unit. A unified CI_k figure is used for the same sector in different cities, regardless of their technological levels, so that greater accuracy can be ensured in observations of industrial internal structure evolution. The carbon emission index per unit output, or CI_k, varies in different industries, with CI_k larger in high-carbon-emission industries and smaller in low carbon emission industries. Cities with a greater proportion of high-carbon-emission industries would have a larger $S_i^k \cdot CI_k$ (value, and a larger $ISCB_i$, assuming high-carbon-emission characteristics.

2.3 Data resources and clarification

This study adopts the administrative divisions issued in 2014, and uses the prefecture-level city as its research unit, with the research period extending from 2000 to 2014. All data were primarily obtained from the statistical yearbooks of prefecture-level cities in the Xuzhou Metropolitan Area. Given the accessibility and comparability of the data, industrial gross output is taken as the main measurement index after normalizing to 1999 prices. The widely used carbon emission coefficient method is used to calculate carbon emissions. In this method, industrial CO_2 emissions are equal to the comprehensive consumption of industrial energy multiplied by the carbon emission coefficient; here, a value of 0.67 t C/tce is adopted, as proposed by the Energy Research Institute of the National Development and Reform Commission. To better highlight the impact of industrial structure on carbon emissions, a presumption is made that all cities in the Xuzhou Metropolitan Area are at an equivalent technological level during the research period, and the data collected in 2014, indicating CO_2 emissions per unit industrial output in different industrial sectors, are used for CI_k in Equation 2.

3 Results and Analysis

3.1 Spatial-temporal heterogeneity of the state of decoupling between industrial development and carbon emission in the Xuzhou Metropolitan Area

According to Table 2, the relationship between industrial development and carbon emission in the general Xuzhou Metropolitan Area remains in a state of relative decoupling, with the DS index showing an increasing trend followed by a decreasing trend; these changes indicate a tendency toward absolute decoupling. From the center to the periphery, the DS index of the central city of Xuzhou has been rapidly decreasing, yet the peripheral seven cities show an increasing DS index from 2.06 to 22.09, indicating a state of coupling. Therefore, there is a general concentric pattern, where the degree of decoupling between industrial structure and carbon emissions gradually diminishes from the center to the periphery. The difference is due to the policies implemented in the East Longhai Industrial Construction and Rejuvenation of the Xuzhou Industrial Base, and the industrial transformation that included intelligent machine industry and bio-pharmacy industry in Xuzhou, which led to constant industrial economic growth. The implementation of the national strategy promoting innovation improved industrial technology and low carbon emissions, and further decoupled industrial growth and carbon emissions. However, the seven surrounding cities have been rapidly industrializing, with a notable dependence on resource-based industries, which increased carbon emissions relative to industrial growth. From the perspective of provincial boundaries, the DS index for the northern Anhui was larger than that for the eastern Henan, which in turn exceeded that for the southern Shandong, whereas the northern Jiangsu had the smallest DS index. Among them, the three regions of the northern Jiangsu, the eastern Henan, and the northern Anhui showed an increase in decoupling, while the southern Shandong evolved from 'relative decoupling II' to 'critical state'. These characteristics were due to the rapid industrial growth in the northern Anhui and the eastern Henan, which had a relatively undeveloped industrial structure and low industrial efficiency. In contrast, the southern Shandong and the northern Jiangsu had comparatively developed economies and low carbon emissions, concomitant with the rapid development of industrial structure. Therefore, they showed a stronger decoupling trend than the northern Anhui and the eastern Henan. In terms of city types, the DS index for recession resource-based cities, i.e., Zaozhuang and Huaibei, was the largest, followed by mature resource-based cities, i.e., Jining and Suzhou, non-resource-based cities, i.e., Lianyungang and Shangqiu, and regenerative resource-based cities, i.e., Xuzhou and Suqian. There was a declining trend in the DS index for these four types, which was especially notable in regenerative resource-based cities that were dominated by non-resource-dependent industries and that promoted low-carbon industrial development. This trend was likely due to the Chinese government vigorously advancing sustainable development transformations in resource-oriented cities, which encouraged the development of lower carbon emissions and resulted in the lowest decoupling indexes. The cities with decreasing resources still depended on resources, but had less development of alternative industries, so their carbon emissions increased with industrial growth. Therefore, their degree of decoupling was the lowest compared with other types of cities, as described previously.

Table 2 The decoupling index quantifying the relationship between carbon emission volume and industrial GDP in Xuzhou Metropolitan Area

Region	2000–2004	2005–2009	2010–2014	2000–2014
Xuzhou	0.73	–0.47	0.35	0.05
Suqian	–0.04	0.14	0.45	0.18
Lianyungang	1.18	0.22	0.59	0.15
Suzhou	3.50	0.01	0.48	0.61
Zaozhuang	0.56	0.45	21.67	0.41
Jining	0.64	0.39	–1.10	0.01
Shangqiu	0.97	0.44	0.07	0.34
Huaibei	0.46	0.56	0.49	0.29
Xuzhou Metropolitan Area	0.78	3.30	0.23	0.15

3.2 Regional heterogeneity in industrial structure and carbon emissions in the Xuzhou Metropolitan Area

3.2.1 The status quo of the industrial structure and carbon emissions

According to Table 3 and Fig. 2, Xuzhou and Lianyungang were dominated by capital- and technology- intensive industries in 2014, while Suqian, Suzhou, Jining, and Shangqiu were dominated by labor-intensive industries, and Huaibei and Zaozhuang were dominated by resource- and labor-intensive industries. The industrial structure level in this metropolitan area declined gradually from the area centered at Xuzhou and Lianyungang to the more peripheral cities. In the same period, carbon emission intensities increased from the center to the periphery, with Suqian at its center, indicating a significantly relationship between industrial structure level and CO_2 emission intensity. In terms of center-to-periphery, in 2014, central cities were dominated by capital- and technology-intensive industries, which accounted for 59.51% of their regional industrial GDP, while peripheral cities were dominated by resource- and labor-intensive industries, taking up 62.49% of the regional total. In the same year, central cities and peripheral cities had carbon emission intensities of 0.99 t/10^4 yuan and 3.07 t/10^4 yuan, respectively, showing that central cities with a more developed industrial structure level boasted lower CO_2 emission intensity, and peripheral cities showed the reverse pattern. In terms of provincial variations, the most lucrative industries in the northern Jiangsu were capital- and technology-intensive industries, generating 57.38% of total output; the three other regions obtained the most revenue from labor-intensive industries, which accounted for more than half of their regional total output. During the same period, the northern Anhui had the greatest industrial CO_2 emission intensity, of 5.98 t/10^4 yuan, followed by the southern Shandong (3.54 t/10^4 yuan), and the eastern Henan (1.34 t/10^4 yuan), with the northern Jiangsu ranking last, with an intensity of 0.71 t/10^4 yuan. Regional differences in the level of development and industrial structure, due to different regional policies, likely led to differences in carbon emission intensity. From the perspective of city types, in the regenerative resource-based cities, capital- and technology-intensive industries dominated industrial growth, accounting for 55.52% of the output total, while resource-intensive industries account for the smallest ratio, 3.91%. In both mature resource-based cities and recession resource-based cities, labor-intensive industries dominated, accounting for 57.72% and 43.90%, respectively, of the total industrial output. In non-resource-based cities, industries were more labor- and capital-intensive; they produced 77.60% of total industrial GDP. During the same period, CO_2 emission intensity in recession resource-based cities was higher than in mature resource-based cities, followed by non-resource-based cities and regenerative resource-based cities; their values were 7.14 t/10^4 yuan, 2.37 t/10^4 yuan, 1.03 t/10^4 yuan, and 0.70 t/10^4 yuan respectively. This relationship indicates that in the leading cities, industries transformed from resource- and labor-intensive to capital- and technology-intensive as the resource availability changed from unlimited to exhausted, and then regenerated; this was then reflected in the CO_2 emission intensity.

3.2.2 Evolution of industrial carbon emissions in the Xuzhou Metropolitan Area and their spatial heterogeneity

Based on the ISCB indices presented in Table 4, which were calculated using Equation (2), the carbon emission characteristics of the industrial structure for all regions and cities across the area from 2000 to 2014 are analyzed.

Table 3 Proportions of factor intensive industry output to gross industrial output in each city (2000, 2014)

City	Resource intensive industry		Labor intensive industry		Capital intensive industry		Technology intensive industry	
	2000	2014	2000	2014	2000	2014	2000	2014
Xuzhou	20.21	4.68	33.61	35.81	30.02	34.52	16.16	24.99
Suqian	6.17	1.38	66.30	56.21	23.01	26.96	4.52	15.44
Lianyungang	9.76	3.29	51.51	33.85	27.61	48.99	11.13	13.88
Huaibei	62.82	24.12	25.03	40.98	11.31	10.25	0.85	24.65
Suzhou	3.54	10.73	48.82	71.80	40.22	9.65	7.43	7.83
Jining	36.30	20.66	35.99	54.26	15.22	9.49	12.48	15.60
Zaozhuang	29.02	15.95	50.94	45.38	12.56	17.37	7.49	21.31
Shangqiu	29.20	26.97	47.50	60.91	17.26	17.79	6.04	15.19

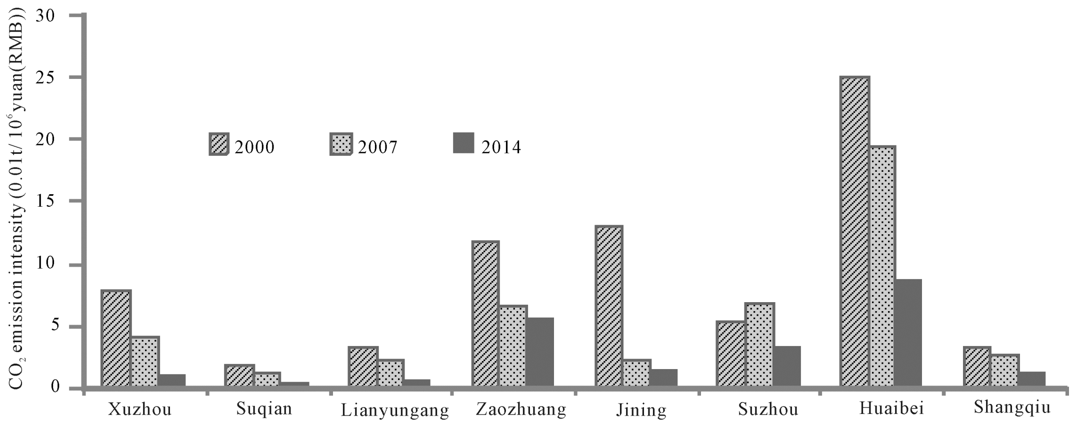

Fig. 2 CO_2 emissions of per capital industrial output in Xuzhou Metropolitan Area

Industrial structure in the Xuzhou Metropolitan Area has become more low-carbon, with the ISCB index decreasing 3.96% annually from 2000 to 2014. From the perspective of a center-periphery comparison, the ISCB index was 0.032 in the central cities and 0.081 in the peripheral cities, the low-carbon trend of the industrial structure decreasing from the center to the periphery. From the perspective of provincial boundaries, the ISCB ranking changed from the southern Shandong > the northern Anhui > the eastern Henan > the northern Jiangsu to the eastern Henan > the southern Shandong > the northern Anhui > the northern Jiangsu over this period. This observation indicates that during the implementation of the Central Henan Urban Agglomeration and Central China Economic Zone, the ISCB index in the eastern Henan declined at the slowest rate, as this region rapidly industrialized, followed by the southern Shandong and the northern Anhui. The ISCB index rankings for cities also changed during this period, shifting from recession resource-based cities > non-resource-based cities > mature resource-based cities > regenerative resource-based cities to recession resource-based cities > mature resource-based cities > non-resource-based cities > regenerative resource-based cities. The non-resource-oriented transformation in regenerative resource-based cities rapidly decreased CO_2 emission intensities, which remained high in recession resource-based cities as pressure from resource exhaustion and from resource-intensive industrial decline increased. The CO_2 emission intensity remained relatively high in non-resource-based cities, due to heavy industrialization, and persisted at a high level, with the slowest rate of decrease being in mature resource-based cities, in which resource-intensive industries remained constant.

Table 4 Changes in the industrial structure characteristic bias (ISCB Index) of Xuzhou Metropolitan Area from 2000 to 2014

City	2000	2005	2010	2014
Xuzhou	0.119	0.337	0.049	0.032
Suqian	0.050	0.033	0.025	0.025
Lianyungang	0.066	0.056	0.060	0.051
Suzhou	0.036	0.176	0.099	0.070
Zaozhuang	0.158	0.158	0.121	0.086
Jining	0.185	0.175	0.146	0.107
Shangqiu	0.158	0.154	0.159	0.113
Huaibei	0.284	0.353	0.218	0.116
Xuzhou Metropolitan Area	0.132	0.180	0.109	0.075

Table 5 shows expanding industries, i.e., those with output growing faster than the regional average and declining industries, i.e., those with output growing more slowly than the regional total, according to industrial data from 2000 to 2014, for all cities within the Xuzhou Metropolitan Area. Electrical machinery and equipment manufacturing was the fastest-growing industry in almost all of the eight cities and produced relatively low carbon emissions, and demonstrated the consistency in industrial structure transformation across the metropolitan area. From the perspective of a center-periphery comparison, the main industrial growth in the central cities was in the bulk chemicals and chemical products manufacturing industry; in the timber processing and wood, bamboo, rattan, palm, and straw products industry; and in the manufacture of precision instruments, office equipment, leisure products, electrical machinery and equipment, and medical products. In comparison, industrial expansion in the peripheral cities was most rapid in ferrous metal smelting, rolling, and processing; in electrical machinery and equipment manufacturing;

Table 5 Top 5 industries in different cities across Xuzhou Metropolitan Area in terms of expansion range from 2000 to 2014

Region	Growing industry	Declining industry
Xuzhou	Pharmaceutical Manufacturing (3.24%), Electrical Machinery and Equipment Manufacturing (4.81%), Timber Processing & Manufacture of Wood, Bamboo, Rattan, Palm and Straw Products (5.01%), Manufacture of Measuring Instruments and Machinery for Cultural Activity and Office Work (5.01%), Manufacture of Raw Chemical Materials and Chemical Products (7.51%)	Manufacture of Beverage (–10.61%), Electricity & Gas & Water (–9.38%), Mining (–6.15%), Manufacture of General Purpose Machinery (–5.37%), Manufacture of Textile (–3.96%)
Suqian	Electrical Machinery and Equipment Manufacturing (3.00%), Manufacture of Articles For Culture, Education and Sport Activities (3.09%), Smelting and Rolling of Non-ferrous Metals (3.31%), Manufacture of Chemical Fibers (5.36%), Computers & Other Electronic Equipment (6.23%)	Manufacture of Textile (–9.13%), Manufacture of Beverage (–8.58%), Farm Food Processing (–7.23%), Manufacture of Non-Metallic Mineral Goods (–3.55%), Timber Processing &Manufacture of Wood, Bamboo, Rattan, Palm and Straw Products) (–2.98%)
Lianyungang	Manufacture of Raw Chemical Materials and Chemical Products (2.46%), Pharmaceutical Manufacturing (2.66%), Smelting and Rolling of Non-ferrous Metals (2.75%), Petroleum Processing & Coking & Nuclear Fuel Processing (4.32%), Smelting and Rolling of Ferrous Metals (14.82%)	Farm Food Processing (–13.45%), Mining (–4.49%), Manufacture of Chemical Fibers (–3.11%), Food Manufacturing (–2.78%), Manufacture of Beverage (–2.51%)
Zaozhuang	Manufacture of Special Purpose Machinery (4.28%), Manufacture of Apparel, Footwear and Cap (4.29%), Manufacture of Raw Chemical Materials and Chemical Products) (4.55%), Manufacture of General Purpose Machinery (4.57%), Electrical Machinery and Equipment Manufacturing (4.78%)	Electricity & Gas & Water (–8.56%), Manufacture of Non-Metallic Mineral goods (–5.80%), Mining (–4.51%), Manufacture of Paper and Paper Products (–2.69%), Food Manufacturing (–2.41%)
Jining	Electrical Machinery and Equipment Manufacturing (1.13%), Manufacture of General Purpose Machinery (1.89%), Manufacture of Metal Products (1.42%), Manufacture of Textile (1.73%), Manufacture of Rubber and Plastics (4.71%)	Electricity & Gas & Water (–11.43%), Mining (–10.01%), Manufacture of Beverage (–4.03%), Food Manufacturing (–3.55%), Manufacture of Special Purpose Machinery (–3.44%)
Suzhou	Manufacture of Apparel, Footwear & Cap (3.44%), Mining (5.44%), Manufacture of Non-Metallic Mineral Goods (7.16%), Timber Processing & Manufacture of Wood, Bamboo, Rattan, Palm and Straw Products (7.86%), Farm Food Processing (14.75%)	Manufacture of Textile (–18.79%), Pharmaceutical Manufacturing (–10.53%), Manufacture of Beverage (–8.62%), Manufacture of tobacco (–4.08%), Manufacture of Chemical Fiber (–4.06%)
Huaibei	Manufacture of Metal Products (4.67%), Electrical Machinery and Equipment Manufacturing (5.03%), Manufacture of General Purpose Machinery (6.36%), Farm Food Processing (10.44%), Manufacture of Special Purpose Machinery (11.19%)	Mining (–27.80%), Manufacture of Textile (–15.15%), Electricity &Gas & Water (–10.90%) Manufacture of Beverage (–2.50%), Petroleum Processing & Coking & Nuclear Fuel Processing (–1.58%)
Shangqiu	Manufacture of Measuring Instruments and Machinery for Cultural Activity & Office Work (2.52%), Mining (2.57%), Electrical Machinery and Equipment Manufacturing (2.64%), Smelting and Rolling of Ferrous Metals (3.74%), Manufacture of Apparel, Footwear & Cap (7.95%)	Electricity & Gas & Water (–9.46%), Manufacture of Beverage (–5.48%), Manufacture of Metal Products (–2.87%), Smelting and Rolling of Non-Ferrous Metals (–2.16%), Farm Food Processing (–2.06%)

Note: the ratio behind each industry refers to the change of the proportion of its output volume to the region's total industrial GDP occurred from 2000 to 2014

and in the manufacture of apparel, footwear and caps, rubber and plastic goods, and manufacture of general purpose machinery. In summary, there was a clear difference in industrial growth within the Xuzhou Metropolitan Area, with the central cities being more capital- and technology-intensive and the peripheral cities more labor- and capital-intensive.

In terms of provincial distribution, expanding industries in North Jiangsu included the smelting and rolling of ferrous metals; bulk chemicals and chemical products manufacturing; electrical machinery and equipment manufacturing; timber processing and wood, bamboo, rattan, palm and straw products; and precision instruments, office equipment, and leisure products. North Anhui had the fastest growth in high-carbon-emissions industries, including agricultural food processing; specialist machinery manufacturing; non-metallic mineral goods manufacturing; timber processing and wood, bamboo, rattan, palm, and straw products; and metal products. In South Shandong, the top five industrial growth sectors were rubber and plastics manufacturing; general machinery, electrical machinery, and equipment manufacturing; apparel, footwear, and caps; and textile manufacturing. In East Henan, the principal industries were large carbon emitters, including the manufacture of precision instruments, office equipment, and leisure products; the mining industry, electrical machinery, and equipment manufacturing; the smelting and rolling of ferrous metals; and apparel, footwear, and cap manufacturing. In summary, North Jiangsu has been actively promoting capital- and technology-intensive industries, whereas South Shandong has focused on labor- and capital-intensive industries, and North Anhui and East Henan have focused on resource-intensive industries and labor-intensive industries, respectively.

From the perspective of city classification, regenerative resource-based cities expanded most rapidly in sectors such as raw chemical materials and chemical products manufacturing; electronic machinery and equipment manufacturing; timber processing and wood, bamboo, rattan, palm and straw products; precision instruments, office equipment, and leisure products; and computers and other electronic equipment. In recession resource-based cities, the fastest-growing industries were specialist machinery manufacturing; general-purpose machinery manufacturing; electronic machinery and equipment manufacturing; production of apparel, footwear, and caps; and bulk chemicals and chemical products manufacturing. In mature resource-based cities, the principal expanding industries were rubber and plastics manufacturing; agricultural food processing; non-metallic mineral goods manufacturing; general purpose machinery; and timber processing and wood, bamboo, rattan, palm, and straw products. Expanding industries in non-resource-based cities were smelting and rolling of ferrous metals; petroleum processing and coking; nuclear fuel processing; pharmaceutical manufacturing; electrical machinery and equipment manufacturing; and bulk chemicals and chemical products. In summary, regenerative resource-based cities have been technology-intensive, and recession resource-based cities have been capital-intensive, while mature resource-based cities and non-resource-based cities have depended on resource-intensive industries, which are major CO_2 producers, explaining the high carbon emissions in these two types of cities.

Generally, most industrial growth in the Xuzhou Metropolitan Area has been in capital- and technology-intensive industries, which have low CO_2 emission intensities and are relatively environmentally friendly. In comparison, resource-intensive industries with high CO_2 emission intensities and that are damaging to the environment have been declining. The Xuzhou Metropolitan Area has been transforming from traditional extensive industries, which are energy-consuming and make little use of technology, toward industries with a high capability for technological innovation and characterized by their much smaller ecological impact.

4 Analysis of Factors Influencing Carbon Emissions During Industrial Structure Transformation in the Xuzhou Metropolitan Area

4.1 Modeling

According to the spatial-temporal characteristics of CO_2 emissions during the transformation of the industrial structure across the Xuzhou Metropolitan Area, as discussed in the previous section, industrial CO_2 emissions are influenced by multiple factors, each exerting different impacts. Therefore, a regression analysis model is established here to evaluate the factors causing the spatial-temporal heterogeneity in carbon emissions during the industrial structure evolution taking place in all cities within the metropolitan area. This analysis is based on their CO_2 emission intensity data. With reference to available documents (He *et al.*, 2011; Wang *et al.*, 2014), industrial structure controls resource utilization, and the structural development reflects the utilization efficiency of resources and the degree of pollution. Therefore, industrial structure can represent regional carbon emissions, and can reflect the influence of regional labor division. The representative indicator is termed the industrial characteristic deviation index. Economic development is another important factor in carbon emissions (Cai *et al.*, 2015). Economic level is the main representation of regional economic development phases. At different phases of economic development, urbanization and industrialization are influenced by the degree of resource utilization, and the volume of carbon emission also varies. The variability can be distinguished based on per capita GDP. The optimization of industrial facilities mainly refers to the construction of facilities for industrial production and environmental protection, which indicates the level of industrial technology and the influence of industrial facilities on carbon emissions. In this study, these concepts are based on the volume of investment of fixed assets. The population factor can be represented by the population size, which is an important influence on carbon emissions (Sun *et al*., 2015). The population size in different regions exerts an influence on the spatial heterogeneity of industrial carbon emissions. Here, population size is taken as recorded at the end of the year. Technological progress is the main influencing factor on carbon emissions. Based on previous studies, it can be represented by technological expenditures. Finally, government intervention reflects the government's ability to regulate carbon emissions and can reveal the influence of social systems on carbon emissions. It is determined using annual fiscal expenditures on carbon emissions, based on previous studies. In summary, the dependent variable in this regression analysis is the CO_2 emission intensity in each city, and the explanatory variables are industrial structure, economic level, the optimization of industrial facilities, population size, technological progress, and government intervention. The model equation is as follows:

$$\ln(CI_{it}) = \beta_1 \ln(ISCB_{it}) + \beta_2 \ln(EL_{it}) + \beta_3 \ln IL_{it} + \beta_4 \ln(PN_{it}) + \beta_5 \ln(STE_{it}) + \beta_6 \ln(GF_{it}) + \varepsilon \quad (3)$$

where CI_{it} is the carbon emission intensity for city i, and in assessing the environmental pressure from economic development, CI_{it} is the carbon emission volume per 10 000 yuan worth of GDP. $ISCB_{it}$ represents the industrial structure characteristic bias, reflecting the regional industrial division for city i, where larger $ISCB_{it}$ indicates a greater specialization in high-carbon-emission industries. EL_{it} refers to the index of economic development level, measured as the per capita GDP of city i. IL_{it} represents the investment scale in the industrial facilities of city i, using the data for industrial fixed asset investments. PN_{it} represents the population size of city i at different development stages, where total population data is taken at the end of the year. STE_{it} represents the scientific and technological level, measured as the expenditures on science and technology. GF_{it} represents the degree of government intervention, measured using the fiscal expenditures of city i.

4.2 Main Influencing Factors

The software STATA12.0 was used to run the model, and the calculated results using a fixed effect model, random effect model, and mixed effects model are compared. The comparison indicates that the Fisher Ratio for the random effect model is of significance only at the 1% confidence level; the fixed effect model also passed the Hausman test, making it a superior choice for this research.

As shown in Table 6, the regression coefficient for the ISCB index for the Xuzhou Metropolitan Area is 0.546. This indicates that, with other conditions constant, an increase in the ISCB index would indicate that industrial carbon emissions were increasing; the industrial structure was evolving towards being more polluting. Government intervention inhibits carbon emissions; therefore, strengthening government regulations would help reduce industrial carbon emissions. In terms of a center–periphery comparison, the ISCB has an inhibitory role on the central cities, but a positive role on the peripheral cities. That is, the green transformation in the central regions has a significant effect; at the same time, government intervention has been more of a restraining force in the peripheral cities than in the central cities. From the perspective of provincial variation, the ISCB index was significantly correlated with carbon emissions in North Anhui, but had little impact in North Jiangsu, East Henan, and South Shandong. The level of economic development had a significant adverse effect on industrial carbon emissions in East Henan, but had no observable effect in the three other regions. The industrial facility level increased carbon emissions in North Jiangsu, whereas it depressed carbon emissions in South Shandong compared to North Anhui and East Henan. Population size significantly intensified industrial carbon emissions in North Jiangsu. Counterintuitively, technological progress increased carbon emissions in North Anhui, which might be due to the fact that scientific and technological investments in this region were mainly for industrial expansion, with little focus on green transformation. Government intervention significantly controlled industrial CO_2 emissions in North Jiangsu and North Anhui, but escalated emissions in East Henan.

In terms of city type, industrial CO_2 emissions in the regenerative resource-based cities were mainly affected by industrial infrastructure investment and population growth, both of which intensified emissions, and by technological progress, which inhibited emissions. This observation suggests that scientific and technological innovation promotes low-carbon emissions in this type of city. In non-resource-based cities, the ISCB index and technological progress were positively correlated with

Table 6 Results of regression analysis on influencing factors of CO_2 emission intensity in Xuzhou Metropolitan Area

Variables	Xuzhou Metropolitan Area	Center-periphery		Provincial boundaries				City types			
		Center	Periphery	Northern Jiangsu	Southern Shandong	Northern Anhui	Easernt Henan	Renewable resource city	Common city	Recession resource city	Mature resource city
ln (ISCB)	0.546***	–1.119**	0.907***	0.334	–1.231	1.381***	0.367	–0.354	0.991*	0.364*	1.308**
	(0.160)	(0.256)	(0.131)	(0.210)	(0.769)	(0.330)	(0.668)	(0.210)	(0.418)	(0.156)	(0.406)
ln (EL)	–0.250	0.408	0.406	–0.078	0.789	0.423	–5.404*	–1.116	–2.737**	–0.262	–1.239
	(0.348)	(2.485)	(0.288)	(0.647)	(0.880)	(1.038)	(1.744)	(0.570)	(0.936)	(0.237)	(1.118)
ln (IL)	–0.005	–1.780	–0.023	0.649*	–3.668***	–1.073	–2.227	0.542*	–1.050*	–0.048	0.078
	(0.229)	(0.782)	(0.225)	(0.310)	(0.893)	(0.713)	(1.150)	(0.274)	(0.424)	(0.333)	(1.148)
ln (PN)	–0.427	–11.86	–0.202	0.920**	1.816	0.200	–6.956	2.833***	–3.258**	–0.393**	0.921
	(0.385)	(18.43)	(0.185)	(0.333)	(1.153)	(0.628)	(8.259)	(0.484)	(1.101)	(0.145)	(5.501)
ln (STE)	0.086	–0.044	–0.075	–0.256	0.098	1.340*	0.103	–0.309*	0.726*	0.047	0.316
	(0.149)	(0.265)	(0.160)	(0.193)	(0.415)	(0.603)	(0.384)	(0.140)	(0.356)	(0.137)	(0.720)
ln (GF)	–0.484*	0.358	–0.588***	–0.738*	0.847	–1.636**	3.865**	–0.197	0.915	–0.157	–0.513
	(0.215)	(1.605)	(0.167)	(0.314)	(0.704)	(0.574)	(1.071)	(0.272)	(0.488)	(0.131)	(0.780)
Constant term	13.33***	98.45	9.614***	-0.721	24.36**	25.25**	75.70	-10.99***	45.88***	10.02***	12.41
	(3.286)	(116.5)	(2.247)	(3.627)	(8.120)	(9.559)	(51.03)	(3.285)	(8.846)	(2.870)	(30.46)
Sample size	120	15	105	45	30	30	15	30	30	30	30
R^2	0.607	0.894	0.609	0.6665	0.8184	0.6160	0.8638	0.8090	0.8232	0.9319	0.6970
F-Ratio	29.71***	20.76***	66.07***	16.40***	22.4***	12.62***	15.79***	29.37***	18.85***	116.7***	8.84***

Note: ***, **, and * represent significance at the confidence level of 1%, 5%, 10% respectively, and those in brackets are *t*-statistics

industrial carbon emissions, while economic development level, industrial facility investment, and population size were significantly negatively correlated. Therefore, the industrial structure and technological innovation in these cities encouraged a trend to high carbon emissions, while upgrading economic development reduced carbon emissions. Recession resource-based cities operated under the combined effect of the ISCB index increasing industrial carbon emissions but of population growth restraining it, and the latter exerted the greater influence. In mature resource-based cities, industrial CO_2 emissions were dominated by the growth of the ISCB index; the resource-based industries were rapidly growing and the industrial structure was characterized by high carbon emissions.

5 Conclusions and Recommendations

5.1 Conclusions

(1) From 2000 through 2014, the relationship between industrial development and carbon emissions in the Xuzhou Metropolitan Area remained in a slightly decoupled state, with a trend toward absolute decoupling. From a spatial perspective, comparing the center to the periphery, a concentric pattern was observed, where the degree of decoupling gradually weakened from the center to the periphery. In terms of the provincial distribution, the decoupling was greatest in North Jiangsu, compared to the three other regions; decoupling decreased in the order South Shandong, East Henan, and North Anhui. From the perspective of city types, the decoupling of regenerative resource-based cities exceeded that of non-resource-based cities, followed by mature resource-based cities, with recession resource-based cities ranking last.

(2) Given the current state of carbon emissions and industrial structure, the Xuzhou Metropolitan Area has become vertically divided; with Xuzhou and Lianyungang at the core, the level of technological advancement diminishes from the center to the periphery. Within the same period, carbon emission intensity has risen according to the same spatial pattern, from the center (Suqian) to the periphery. This highlights the marked negative correlation between technological level and carbon emissions in the Xuzhou Metropolitan Area.

(3) From 2000 to 2014, the ISCB index in the Xuzhou Metropolitan Area first increased and then decreased, indicating the weakening role of industrial structure in intensifying carbon emission. From the center to the periphery, the trend to low carbon emissions becomes less notable, assuming a concentric pattern. From the perspective of provincial variation, the ISCB

index in East Henan decreased at the slowest rate, followed by South Shandong and North Anhui, with North Jiangsu remaining at the lowest level. In terms of city types, the recession resource-based cities had the largest ISCB index, mature resource-based cities ranked second, non-resource-based cities third, and regenerative resource-based cities last; this ranking highlights the significant difference in terms of achievements of reduced carbon emissions between cities at different resource exploration stages.

(4) From the perspective of industrial heterogeneity, the industrial structure of the Xuzhou Metropolitan Area has rapidly evolved from resource- and labor-intensive to capital- and technology-intensive, indicating a greater tendency for CO_2 emissions reduction. From the center to the periphery, the central cities showed the fastest expansion in technology-intensive industries and a significant reduction in carbon emissions volume, while the peripheral cities remained dominated by resource- and labor-intensive industries and displayed a correspondingly greater carbon emission intensity. This observation indicates that in the growing resource-based metropolitan area, industrial structure improvements have been vertically divided: rapidly improving in the central cities and slowly improving in the peripheral cities, which has led to a greater reduction in carbon emissions in the central cities than in the peripheral cities. In terms of provincial variation, North Jiangsu has been dominated by capital- and technology-intensive industries, South Shandong by labor- and capital-intensive industries, and North Anhui and East Henan by resource- and labor-intensive industries, reflecting a spatial difference in industrial transformation due to varying industrialization stages and development policies. In terms of city types, regenerative resource-based cities have vigorously advanced technology-intensive industries, recession resource-based cities have primarily focused on capital-intensive industries, while both mature resource-based cities and non-resource-based cities have been dominated by resource-intensive industries with high carbon emission intensity. Therefore, cities at different resource exploitation stages have correspondingly varying industrial structure improvement levels and carbon emission effects.

(5) Based on the regression analysis, industrial structure had a significant impact on carbon emissions in the Xuzhou Metropolitan Area and has been the leading factor causing heterogeneity in CO_2 emission intensities. This is particularly true for peripheral cities that have been constrained by labor division and by industrialization level; they will likely remain driven for some time by resource- and labor-intensive industries that can cause heavy pollution. Industrial structure heterogeneity has remained the decisive factor, accounting for the differences in low-carbon transformation across the Xuzhou Metropolitan Area. From the perspective of provincial variation, industrial structure and technological progress had observable positive correlations with industrial carbon emissions in the northern Anhui and economic growth was a major factor inhibiting industrial carbon emission in the eastern Henan. Government intervention reduced carbon emissions in the northern Jiangsu and the northern Anhui, but had the reverse effect in the eastern Henan. Thus, industrial carbon emissions in different cities have been influenced by a variety of factors.

5.2 Recommendations

Targeting the one-way flow pattern of resources, production and waste, we provide the following suggestions for industrial restructuring and layout optimization. These suggestions are based on: building a low carbon recycling industry system, emphasis on carbon sink functions, the driving forces of low-carbon innovation technology, and enforcing policies in green development to establish a controlled system. First, industrial network in circle economy should be constructed. Based on the concepts of vertical closure, horizontal coupling, and regional integration, an industrial ecological network system oriented toward low-carbon industries should be introduced; this can be realized through industrial ecological parks specializing in high-tech and high-value-added industries, such as electrical machinery and equipment manufacturing, pharmaceutical manufacturing, and equipment manufacturing; this should extend the industrial focus downstream along the value chain. Second, we should enhance the environmental carrying capacity. Intensifying environmental governance should be focused on addressing industrial environmental pollution and the functional reconstruction of coalmine subsidence areas. The Green Action Plan, "Marching into the Barren Hills Again" should be implemented to increase carbon sink function. Third, we should facilitate innovations in low-carbon technology.

Equipment upgrades and process innovation, in particular, innovations that lead to cleaner production: should be emphasized. More efforts should be made to transform traditional industries and develop high-tech industry, so that industrial resource consumption and pollutant emission intensity can be reduced. Central cities should work to raise the proportion of high-tech industries and producer services in their industrial system. Peripheral cities should focus more on transforming traditional industries, and increase their potential for carbon emission reduction. Fourth, we should improve the population distribution and population quality. The government should adhere to the law of urbanization so as to turn farmers into urban citizens, and improve the population distribution according to major functions in different areas. Furthermore, the government can foster citizen awareness of green development and low-carbon development, and promote preferences for low-carbon products. Finally, we should improve the control system for ensuring low industrial carbon emissions. After taking into consideration the features of a resource-based, provincial bordering metropolitan area, the government should adopt industrial policies that favor industries that are quality- and benefit-oriented, science- and technology-based, and resource-efficient, which will decrease CO_2 emissions. The government should also regularly issue a list of categories for promoting, restricting, and phasing out industries to guide the industrial transition to low carbon emissions in the Xuzhou Metropolitan Area.

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