Industrial Agglomeration and Carbon Neutrality in China: Lessons and Evidence

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Abstract: How does the agglomeration economy affect carbon emissions? Does it hinder China's zero-carbon emissions and carbon neutral goals? This study explored the impact of industrial agglomeration on carbon emissions and spatial spillover effects by expanding the output density theoretical model of Ciccone & Hall. The main findings are as follows: (1) Industrial labor and technology agglomerations increase regional carbon emissions, while industrial output agglomeration reduces emissions in the immediate term. Industrial capital agglomeration has no significant immediate effect on carbon emission. (2) Industrial output and technology agglomerations have significant lag effects. Output agglomeration increases carbon emissions, while technology agglomeration reduces emission levels. (3) The impact of industrial output agglomeration on regional carbon emissions shifts from a positive inhibitory effect into a negative aggravating effect. In comparison, industrial technology agglomeration transitions from increasing carbon emissions in the immediate term into having a suppressing effect in the long term. (4) There are significant regional differences in the impact of industrial output and capital agglomerations, while industrial labor and technology agglomerations showed no significant regional difference. The results are important in developing policies and strategies of the economy and the environment.

Keywords: industrial agglomeration；carbon neutrality；carbon emissions；industrial labor agglomeration; industrial technology agglomeration; industrial output agglomeration; industrial capital agglomeration; spatial effect

1 Introduction

Due to climate change, countries around the world are making various efforts to reduce carbon emissions and achieve carbon neutrality(Rehfeldt et al. 2020; Subramanian et al. 2020). On September 22, 2020, during the 75th United Nations General Assembly, the Chinese government announced that it would adopt policies and measures that would enable the country to reach its carbon emission peak no later than 2030 and achieve carbon neutrality by 2060(Zhang and Li 2021) . In order to become carbon neutral by 2060, China must have near-zero emissions by 2050 and build an energy system with green and renewable energy (Sun et al. 2018; Alam and Murad 2020). The key to achieving this goal depends on the significant transformation of the country's economic development, industries, and energy system.

In China, industrial agglomeration characterized by agglomeration economy is the main factor promoting economic development. While industrial agglomeration promotes economic growth, it also brings environmental challenges and pollution problems, including increased carbon emissions(Vinh and Khalid 2020; Hong et al. 2020; Alaniz et al. 2020). In this context, what is the impact of industrial agglomeration on carbon emissions? Will industrial agglomeration have spatial spillover effects and lagging effects on carbon emissions? Does industrial agglomeration hinder the goal of carbon neutrality? The answers to these questions can help explain the relationship between industrial agglomeration and pollution control and support in developing policies that would benefit economic development while strengthening carbon control.

Whether industrial agglomerations reduce the overall carbon emissions remains to be highly controversial. Some scholars have found that energy conservation and emission reduction are not the goals of industrial agglomeration. The endogenous power of industrial agglomeration is to realize the sharing of infrastructure, improve the matching efficiency of production factors, and promote the spatial spillover of professional knowledge, thereby improving the production efficiency of enterprises (Bie et al. 2017; Ding et al. 2019). Some studies in China have found that industrial agglomerations fail to promote carbon emission reduction and may even distort existing allocations of production factors, which further exacerbate carbon emissions. Zhang and Wang(2014) believe that economic agglomeration can aggravate environmental degradation and that pollution has a reverse inhibitory effect on economic agglomeration(Zhang and Wang 2014). Ya and Meng (2019) found that industrial agglomeration has significantly increased carbon emissions for some regions while also having a restraining effect on carbon emissions of neighboring regions(Ya and Meng 2019). Zhang et al.(2019) found that the increase in industrial agglomeration has resulted in the rise of environmental pollution(Zhang et al. 2019). Dong et al.(2020) found that industrial agglomeration leads to pollution agglomeration at the national level, although the impact varies in size for different provinces(Dong et al. 2020). Ding et al.(2020) believe that although environmental regulations promote urban industrial agglomeration, industrial agglomerations have significantly increased the intensity of urban carbon emissions, which eclipse the positive impact of regulations in reducing emissions to a certain extent(Ding et al. 2020). Lu et al.(2021) found that while there is a significant positive relationship between the agglomeration of primary and secondary industries and haze pollution in the Bohai Sea economic region, the agglomeration of the tertiary industry has no significant impact on haze pollution(Lu et al. 2021). Li et al.(2021) found that industrial agglomeration has significantly aggravated local and nearby haze pollution at the urban level(Li et al. 2021).

On the other hand, New Economic Geography believes that industrial agglomerations, as compact economic spaces, can improve enterprises' production and resource utilization efficiencies with externalities as the link(Li and Zhang 2020). It is believed that industrial agglomeration may aggravate environmental pollution within a certain period, but once it reaches the threshold, industrial agglomeration benefits the environment. Yan et al.(2011) found that the development of industrial clusters in the short term is conducive to reducing environmental pollution. They concluded that the gathering of industrial labor and capital aggravates haze pollution, while the gathering of industrial output reduces haze pollution(Yan et al. 2011). Yang (2015) found that the impact of industrial agglomeration on environmental pollution has significant threshold characteristics. When the level of industrial agglomeration is below the threshold, it can aggravate environmental pollution; when the level is above the threshold, it is able to reduce pollution levels(Yang 2015). Chen et al.(2017) found that industrial agglomeration reduces industrial carbon dioxide levels, which can help realize the emission reduction targets in China's prefecture-level cities(Chen et al. 2017). Zhang et al.(2018) concluded that industrial agglomeration in Henan Province is conducive to breaking the lock-in of high-carbon industries and reducing energy consumptionZhang et al.(2018). Zheng and Lin(2018) found that for China's paper industry, industrial agglomeration can improve energy efficiency and reduce environmental pollution after it crosses the threshold(Zheng and Lin 2018). Li et al.(2019) found that the emission reduction effect of industrial agglomeration is limited and that there is a double threshold effect(Li et al. 2019). Zhu and Xia(2019) found an inverted U-shaped relationship between industrial agglomeration and environmental pollution under China's New Urbanization(Zhu and Xia 2019). Liu et al.(2019) also identified an inverted U-shaped relationship between industrial agglomeration and industrial pollution at the city-level(Liu et al. 2019). Chen et al.(2020) found an inverted U-shaped relationship between industrial agglomeration and pollutants, such as sulfur dioxide and dust, and a threshold effect between industrial agglomeration and environmental benefits in

China's 259 citiesChen et al.(2020)Chen et al.(2020)Chen et al.(2020). Guo et al.(2020) suggest a U-shaped relationship between industrial agglomeration and green development exists in Northeast China(Guo et al. 2020). They believe that both specialized industrial agglomeration and diversified industrial agglomeration have threshold effects on environmental pollution in the Yangtze River Delta.

Some scholars believe that the relationship between industrial agglomeration and environmental pollution (carbon emissions) is uncertain. Yang(2017) argues that due to different scenario factors, the impact of urban industrial agglomerations on carbon emission efficiency varies (Yang 2017). Wang and Wang (2019) suggest that the relationship of industrial agglomeration with sulfur dioxide and dust pollutants is heterogeneous in urban China(Wang and Wang 2019). Shen and Peng(2020) used the spatial panel model to analyze the impact of industrial agglomeration externalities on environmental efficiency. Their study found that different systems and degrees of industrial agglomeration can have varying emission reduction effects(Shen and Peng 2020).

Previous studies have explored the impact of industrial agglomeration on environmental pollution at different levels. However, after conducting an extensive review of existing literature (see Table 1), we found that there are still major shortcomings with the current research. First, few studies have directly studied industrial agglomeration and carbon emissions. Studies have mainly focused on analyzing the impact of industrial agglomeration on environmental pollution at the macro-level perspective. But different types of pollutants have different characteristics. For example, carbon emissions have strong transboundary and spatial spillover effects, which may not be significant for other pollutants, such as industrial smoke and dust. When studying the impact of industrial agglomeration on pollution levels, the type of pollutants and their characteristics must be fully considered. Second, most studies use only a single indicator when analyzing the impact of industrial agglomeration on environmental pollution, often overlooking the differential impact of different agglomeration structures. Different industrial agglomeration characteristics have differentiated effects on the environment. Industrial agglomerations with labor as the main feature would impact pollution levels differently compared with capital and technology type agglomerations. Third, the impact of industrial agglomeration on environmental pollution exhibits a particular lag, which has often been neglected in previous research. This impact is often not obvious during the formation of industrial agglomerations and becomes more pronounced over time. These cumulative effects and lagging characteristics have to be considered when exploring the overall impact of industrial agglomeration on the environment.

Table 1 Studies on different types of environmental regulation and carbon emissions

Authors	Country	Time	Methods	Key findings
Yang(2015)	30 provinces in China	2004-2011	Threshold model	Industrial agglomeration first aggravated environmental pollution, and after crossing the threshold, it reduced environmental pollution.
Chen et al.(2017)	187 Chinese prefecture-level cities	2005–2013	General panel model	Industrial agglomeration intensifies urban carbon emissions.
Ya and Meng (2019)	panel data of China	2004-2016	spatial econometric model	Industrial agglomeration significantly increases carbon emissions in the region while inhibits the carbon emissions in the neighboring areas.
Zhang et al.(2018)	18 cities in Henan Province	2005-2015	spatial panel regression model	Industrial agglomeration helps lift industrial carbon lock.
Zheng and Lin(2018)	29 provinces of the paper industry in China	2000-2005	Threshold regression model	There is a threshold effect between industrial agglomeration and environmental pollution.
Zhang et al.(2019)	30 provinces in China	2003-2016	optimal model structure selection method	The increase in industrial agglomeration has increased environmental pollution
Li et al.(2019)	30 provinces in China	2009–2016	Threshold regression model	There are double threshold effects between industrial agglomeration and carbon emissions.
Zhu and Xia(2019)	30 Chinese prefecture cities	2005-2015	equilibrium model	There is a threshold effect between industrial agglomeration and environmental pollution.
Wang and Wang(2019)	281prefectural-cities in China	2003–2010	simple pooled OLS regression	The impact of industrial agglomeration on different pollutant emissions is heterogeneous
Chen et al.(2020)	China's 259 cities	2007-2016	spatial econometric model	There is a U-shaped relationship between industrial agglomeration and sulfur dioxide and dust.
Pei et al.(2020)	the Yangtze River Delta	2006- 2016	Copeland–Taylor Model	There is a threshold effect between specialized agglomeration and diversified agglomeration and environmental pollution
Dong et al.(2020)	36 segments of the industry in 29	2000 -2016	spatial panel model	There is a U-shaped relationship between industrial agglomeration and environmental

	provinces of China from			efficiency.
Shen and Peng (2020)	29 provinces in China	2000 -2018	spatial panel model	Different agglomeration degrees and means may be matched with different environmental effects
Ding et al.(2020)	282 prefecture-level cities	2003-2017	simple pooled OLS regression	Industrial agglomeration intensifies urban carbon emissions by suppressing the role of environmental regulations

To address these current research limitations, this study explores the overall impact and lag characteristics using different type of industrial agglomeration on carbon emissions. Using provincial panel data of 30 provinces in China from 2002 to 2018, this study comprehensively analyzed the regional variations of this influence. The contributions of this study are as follows. First, based on internal structure, industrial agglomerations were analyzed using four aspects: industrial output agglomeration, industrial labor agglomeration, industrial capital agglomeration, and industrial technology agglomeration. Each agglomeration aspect was analyzed separately to provide a more comprehensive overview of the impact of industrial agglomeration on carbon levels. Second, this study fully considered the transboundary impact and spatial spillover characteristics of carbon emissions and used spatial econometric models in analyzing the effects. Third, this study explored the lag effect and cumulative effects of industrial agglomeration on regional carbon emissions and examined the regional differences. The results of this study can be used to provide an explanation for the inconsistent research conclusions in the existing research and provide a reference for future research. The full text is arranged as follows. We first reviewed studies on industrial agglomeration and carbon emissions (see Figure 1) and found deficiencies with the current research. In the method section, the research methods and variables are described. In the results section, we summarize the findings of the spatial correlation analysis and the direct, lagging, and regional impacts of industrial agglomeration on carbon emissions. In the discussion section, we examine and contextualize the results, and in the conclusion section, we provide the conclusions and policy recommendations.

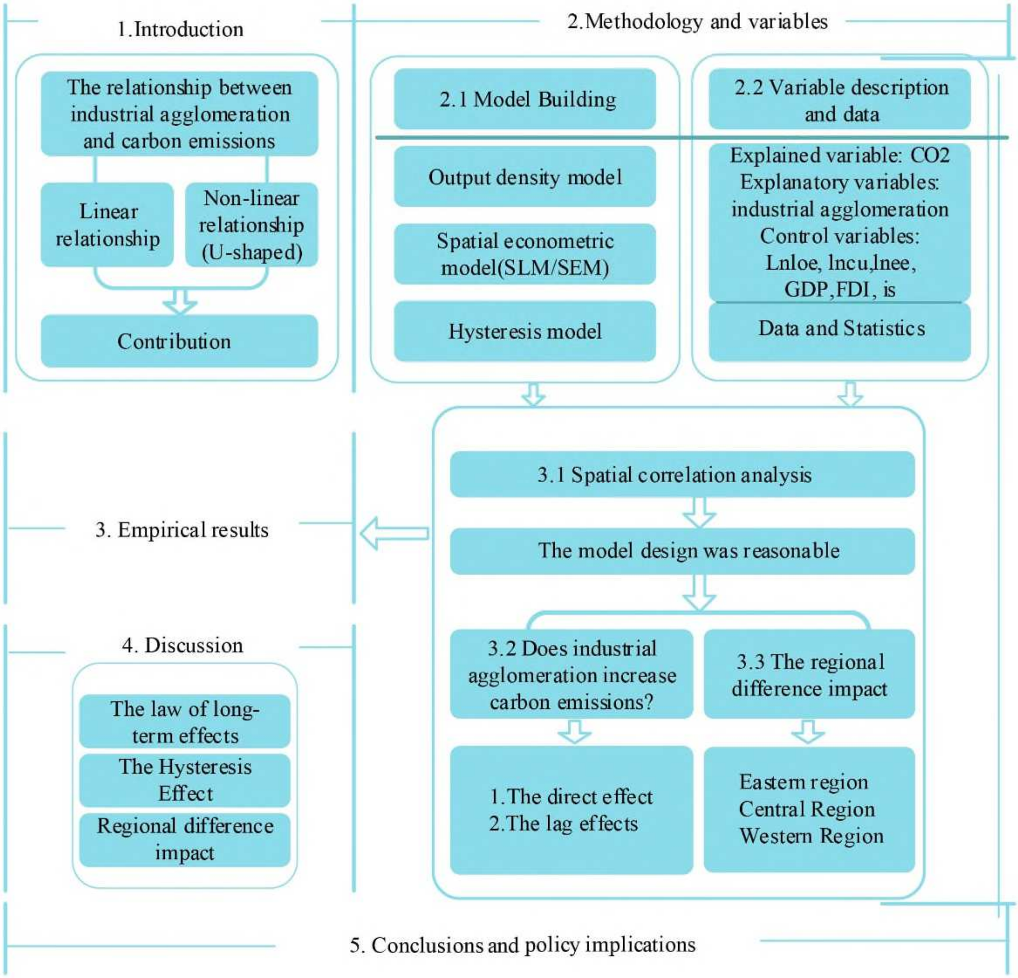

Fig. 1. The research framework of this study

2. Material and methods

2.1 Model Building

Drawing lessons from Dong et al.(2015) incorporating environmental factors into the industrial production model and using carbon emissions as a by-product of industrial output, we incorporated the environment as an output factor into the output density model of Ciccone & Hall (1996) (Ciccone and Hall 1996) (Ciccone and Hall 1996). We used the theoretical mechanism of action between industrial agglomeration and carbon emissions. The model is as follows:

$$\frac{CO2_i}{A_i} = \theta_i \left[\left(\frac{N_i}{A_i}\right)^{\beta} \left(\frac{K_i}{A_i}\right)^{\gamma} \left(\frac{E_i}{A_i}\right)^{1-\beta-\gamma} \right]^{\alpha} \left(\frac{CO2_i}{A_i}\right)^{\frac{\lambda-1}{\lambda}} \quad (1)$$

where, $CO2_i$、N_i、K_i and E_i represent total carbon emissions, industrial employment scale, industrial capital scale, and industrial energy consumption of area i, respectively. $CO2_i/A_i$,

N_i/A_i, K_i/A_i, and E_i/A_i represent per unit area of carbon emissions, industrial labor density, industrial capital density, and industrial energy consumption density of area i, respectively. θ_i is the production efficiency of area i; A_i is the total area of area i; α is the return to scale of industrial labor, capital, and energy per unit area. When 0<α<1, the return to scale is decreasing; when α=1, the return to scale is unchanged; when α>1, the return to scale is increasing. β is the contribution rate of industrial labor output per unit area in region i, γ is the contribution rate of industrial capital-output per unit area in region i, 0<β≤1,0<γ≤1. λ is the parameter of carbon emission concentration. When λ>1, carbon emission has externalities to the regional economy. After converting Equation (1), we get:

$$\left(\frac{CO2_i}{A_i}\right)^{\frac{1}{\lambda}} = \theta_i\left[\left(\frac{N_i}{A_i}\right)^{\beta}\left(\frac{K_i}{A_i}\right)^{\gamma}\left(\frac{E_i}{A_i}\right)^{1-\beta-\gamma}\right]^{\alpha} \quad (2)$$

Equation 2 is then converted to obtain:

$$\left(\frac{CO2_i}{A_i}\right)^{\frac{1}{\lambda}} = \theta_i(N_i^{\beta}K_i^{\gamma}E_i^{1-\beta-\gamma})_i^{\alpha}\left(\frac{1}{A_i}\right)^{\alpha} \quad (3)$$

Equation 3 can then be converted to:

$$\left(\frac{CO2_i}{A_i}\right)^{\frac{1}{\lambda}} = \theta_i\left[\left(\frac{K_i}{N_i}\right)^{\gamma}\left(\frac{E_i}{N_i}\right)^{1-\beta-\gamma}\right]^{\alpha}\left(\frac{N_i}{A_i}\right)^{\alpha} \quad (4)$$

such that $K_i/N_i = k_i$ denote the industrial investment per labor, and $E_i/N_i = e_i$ denote the energy input per labor. After converting Equation (4), we get:

$$\left(\frac{CO2_i}{A_i}\right)^{\frac{1}{\lambda}} = \theta_i(k_i^{\gamma}e_i^{1-\beta-\gamma})^{\alpha}\left(\frac{N_i}{A_i}\right)^{\alpha} \quad (5)$$

Taking the logarithm of both sides of Equation (5), we get the following:

$$\frac{1}{\lambda}\ln\left(\frac{CO2_i}{A_i}\right) = \ln\theta_i + \alpha\gamma\ln k_i + \alpha(1-\beta-\gamma)\ln e_i + \alpha\ln\frac{N_i}{A_i} \quad (6)$$

From Equation (6), we get the following:

$$\ln\frac{CO2_i}{A_i} = \lambda\ln\theta_i + \lambda\alpha\gamma\ln k_i + \lambda\alpha(1-\beta-\gamma)\ln e_i + \lambda\alpha\ln\frac{N_i}{A_i} \quad (7)$$

In Equation (7), $\ln(CO2_i/A_i)$ indicates unit carbon emissions, $\ln\theta_i$ indicates industrial production efficiency, $\ln k_i$ and $\ln e_i$ represent the efficiency of industrial resource use, and $\ln N_i/A_i$ represents industrial labor concentration.

The resulting equation shows an interactive relationship between carbon emissions and industrial efficiency and industrial agglomeration. This is consistent with the findings of Ya and Meng (2019), Dong et al. (2020), and Lu et al. (2021) that found industrial agglomeration as a major factor leading to environmental problems. These studies also suggest that carbon emissions have spatial spillover characteristics and that the spatial measurement model can be used to construct the empirical model. Based on the spatial lag model and the spatial error model of Anselin(1995)(Anselin 1995), this paper constructs an SLM that affects carbon emissions by industrial agglomeration. The SEM model is as follows:

$$\ln CO2_{it} = \rho w \ln CO2_{it} + \alpha_0 + \alpha_1 \ln IA_{it} + \alpha_2 \ln X_{it} + \varepsilon_{it} \quad (8)$$

$$\ln CO2_{it} = \beta + \beta_1 \ln IA_{it} + \beta_2 \ln X_{it} + \varepsilon_{it}\ ,\ \ \varepsilon_{it} = \lambda w \ln CO2_{it} + u_{it} \quad (9)$$

where $\ln CO2_{it}$ represents carbon emissions, $\ln IA_{it}$ represents industrial agglomeration, and $\ln X_{it}$ represents the collection of control variables. To investigate the lagged effect of industrial agglomeration on carbon emissions, we added the lagged 1st and lagged 2nd of industrial agglomerations to equations (8) and (9), and formed the SLM and SEM models to analyze the lagged effects:

$$\ln CO2_{it} = \rho w \ln CO2_{it} + \alpha_0 + \alpha_1 \ln IA_{it} + \alpha_2 \ln IA_{it-1} + \alpha_3 \ln IA_{it-2} + \alpha_4 \ln X_{it} + \varepsilon_{it} \quad (10)$$

$$\ln CO2_{it} = \beta + \beta_1 \ln IA_{it} + \beta_2 \ln IA_{it-1} + \beta_3 \ln IA_{it-2} + \beta_4 \ln X_{it} + \varepsilon_{it}\ ,\ \ \varepsilon_{it} = \lambda w \ln CO2_{it} + u_{it} \quad (11)$$

2.2 Variable description and data

2.2.1 Carbon emissions

Based on the “Guidelines for National Greenhouse Gas Inventories” issued by the IPCC in 2006, we measured carbon dioxide emissions based on emissions from different energy sources, which include coal, hard coke, crude oil, gasoline, kerosene, diesel, fuel oil, and natural gas (Wu 2015; Yang et al. 2020). We calculated consumption from various energy sources and multiplied each with the respective emission coefficient, then added the values to obtain the total carbon emissions (see Fig.2). The carbon emission coefficients were obtained from the China Energy Statistical Yearbook (2008), and the various energy sources were standardized before calculations. The calculation method is as follows:

$$C_{i,t} = \sum (E_{irt} \bullet \eta_r) \quad (12)$$

where C_{it} is the total amount of carbon dioxide emissions of province i in year t; E_{irt} denotes the consumption of energy r in year-t of province i, and η_r is the carbon emission coefficient of the r-th type of energy.

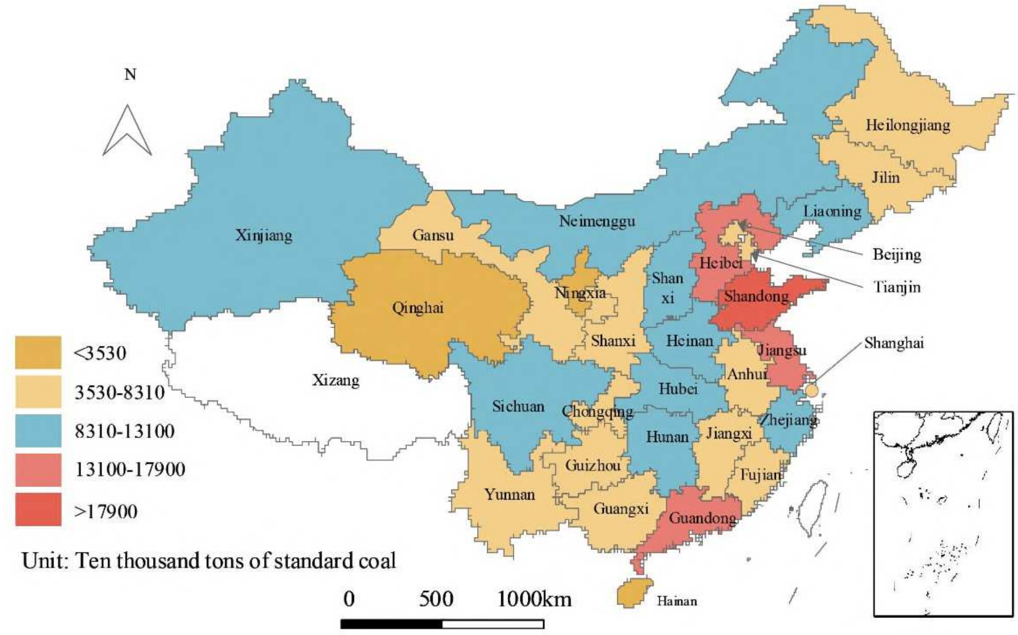

Fig.2. carbon emissions in 2018

2.2.2 Industrial agglomeration

Production factors have considerable influence on the development of industrial agglomeration. Labor, capital, and technology are the primary production factors affecting economic agglomeration (Dong et al. 2015; Shen and Peng 2020). In this study, the degree of industrial agglomeration was first measured as a whole by industrial output aggregation (OA), measured as the scale of industrial output per unit area (Dong et al. 2015). Then, industrial agglomeration was evaluated from three aspects: industrial labor agglomeration (LA), industrial capital agglomeration (CA), and industrial technology agglomeration (TA). Industrial labor agglomeration (LA) is the number of industrial employees per unit area, industrial capital agglomeration (CA) is the scale of industrial capital stock per unit area, and industrial technology agglomeration (TA) is R&D investment per unit area (Huang et al. 2019; Yao et al. 2020).

2.2.3 Control variables

Industrial energy consumption directly affects industrial solid waste and total carbon emissions

(Afridi et al. 2019). At the same time, the level of carbon emissions in a region is also affected by the local economic development level (GDP), Foreign direct investment (FDI) level, and industrial structure (Is). The higher the level of regional economic development and the greater the total economic volume, the more energy is consumed and the greater the carbon emissions (Chen et al. 2019; Yang et al. 2020)(Chen et al. 2019; Yang et al. 2020)(Chen et al. 2019; Yang et al. 2020)(Chen et al., 2019; Yang et al., 2020)[37, 41]. The level of foreign investment reflects the degree of economic openness in a region. Economic openness and technology can significantly affect industrial agglomeration and impact the environment (Yang et al. 2018). The proportion of the secondary industry in the industrial structure can also have a considerable impact on energy consumption and pollution emissions. As a high-energy consumer, the secondary industry sector is the primary source of carbon emissions (Dong et al. 2020). The level of economic development is measured by per capita GDP, FDI by actual foreign investment, and the industrial structure by the proportion of the secondary industry sector.

Data from 30 provinces in China from 2002 to 2018 were used as the research sample. The data were obtained from the "China Industry Yearbook", "China Statistical Yearbook", "China Environment Statistical Yearbook", "China Population and Employment Statistical Yearbook", and provincial statistical yearbooks. The missing data was calculated using the mean value method. In data processing, the logarithm of individual variables was used to eliminate the difference in variable measurement units. The definition and description of each variable are shown in Table 2.

Table 2 Descriptive statistical analysis of variable

Variables	Definition	unit	Minimum	Maximum	Mean	Std. Deviation
$\ln co_2$	Carbon emissions	Ten thousand tons of standard coal	6.0000	11.0000	8.8098	0.8893
lnOA	industrial output agglomeration	Ten thousand yuan/km^2	0.0000	10.0000	5.4725	1.7276
lnLA	Industrial labor agglomeration	person/km^2	-1.0000	7.0000	3.3922	1.5991
lnCA	Industrial capital agglomeration	Ten thousand yuan/km^2	1.0000	9.0000	5.4804	1.6545
lnTA	Industrial technology agglomeration	yuan/km^2	5.0000	17.0000	11.1176	2.2596
lnEE	Industrial energy consumption	Ten thousand tons of standard coal	2.0000	5.0000	2.9961	0.6780
lngdp	The level of economic development	yuan	8.0000	12.0000	10.2098	0.8509
lnFDI	Foreign direct investment	Billion	-1.0000	8.0000	5.0373	1.7180
lnIS	Industrial structure	%	2.0000	4.0000	3.8059	0.4057

3 Results

3.1 Are there spatial spillover characteristics of carbon emissions?

Before analyzing the spatial econometric model, we first determined whether the explanatory variables have spatial spillover characteristics. To gauge spatial autocorrelation characteristics, exploratory data analysis methods were used in calculating the global spatial autocorrelation index (*Global Moran's I*) and Moran scatter plot of carbon emissions. Figure 3 reports the global Moran's I index of carbon emissions from 2002 to 2018. The average Moran's I for carbon emissions is 0.2450, and both indexes are significant at the 5% level. As shown in Figure 4, most of the Moran's I for carbon emissions falls in the first and three quadrants of the scatterplot. For 2002, 2007, 2012, and 2018, more than 60% of the areas were in the first three quadrants with significant and positive spatial spillover characteristics. This suggests that carbon emissions in these regions exhibit some spillover effects on neighboring regions. This finding is consistent with the research conclusions of Wu (2015) and Yang et al. (2018). Therefore, when analyzing the impact of industrial agglomeration on carbon emissions, spatial factors must be considered.

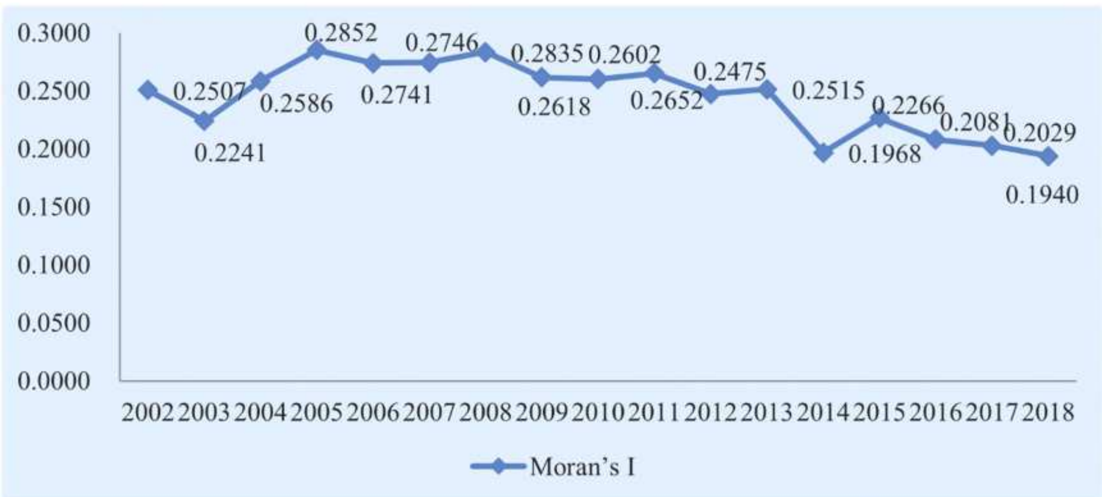

Fig. 3. Moran's I values of carbon emissions in China from 2002 to 2018

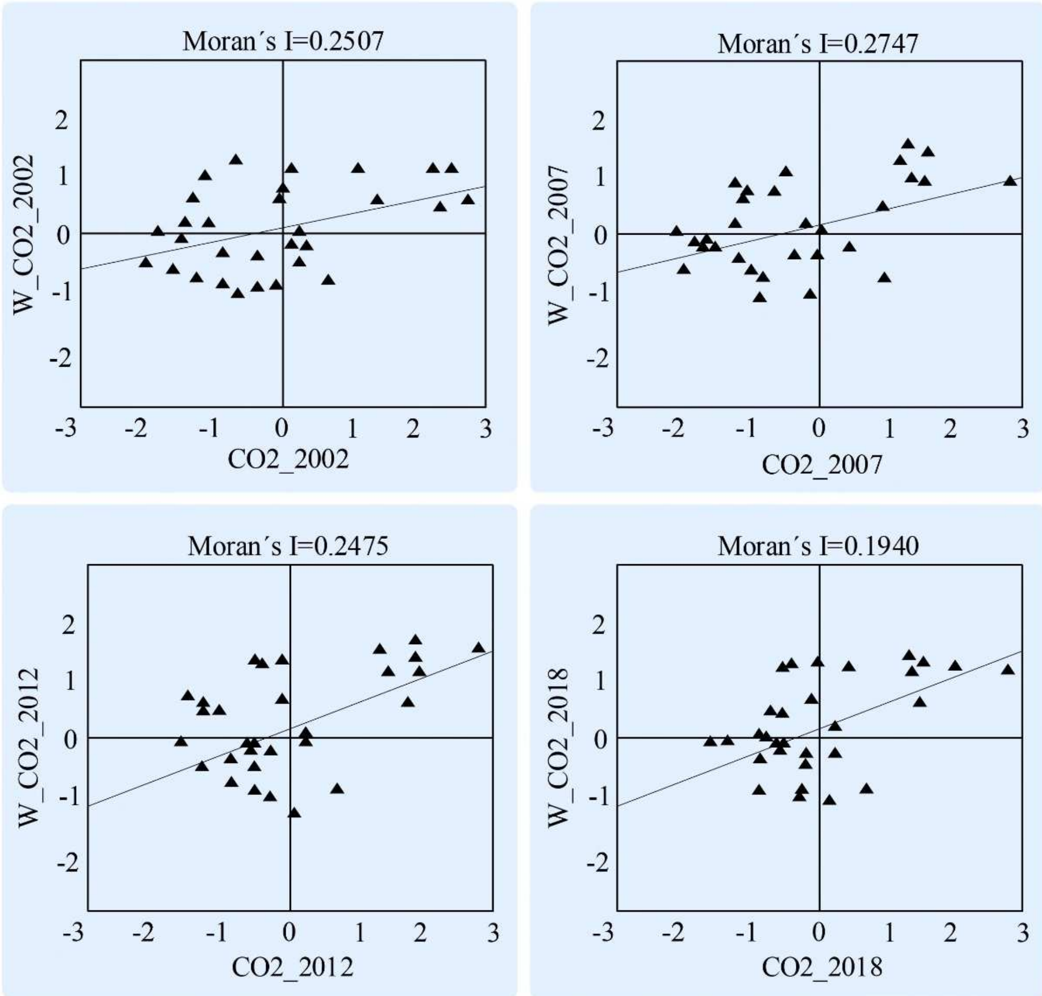

Fig.4. Moran scatterplots of carbon emissions for 2002, 2007, 2012, and 2018

3.2 Does industrial agglomeration increase carbon emissions?

We first performed OLS regression using the LM test and the robust LM test for SLM and SEM models for model selection. The p-values of the LM test and robust LM test for the SLM model are significant, while not significant for the SEM model. We also found that the fixed-effects model yielded better results than the random-effects model. Based on these preliminary results, the SLM model with fixed effects was used in the remainder of this study. To avoid multicollinearity problems, we conducted separate regression analyses on the four indicators of industrial agglomeration. Table 3 summarizes the analysis results of the impact of industrial agglomeration on carbon emissions.

The results show that industrial output agglomeration effectively suppressed regional carbon emissions and exhibited a significant lag effect. Table 4 reports the impact of industrial output agglomeration on carbon emissions. The coefficient for industrial output agglomeration is negative and statistically significant at the 5% level, indicating that industrial output agglomeration reduces carbon emissions. The agglomeration of industrial output generally reflects the level and degree of industrial agglomeration in a region. The negative coefficient suggests that the industrial output agglomeration has realized the optimal allocation of regional resources, improved resource utilization efficiency, and reduced regional environmental pollution. This finding is in line with the research conclusions of Yan et al. (2011), Dong et al. (2015), Yang (2015), Chen et al. (2017), Zheng and Lin (2018), Liu et al. (2019), and Guo et al. (2020). The results also suggest that industrial agglomeration achieved combined regional and resource agglomeration advantages and was able to improve the environment while also promoting economic development.

The coefficient for industrial output agglomeration with one lag period is positive and significant at the 5% level. The coefficient for industrial output agglomeration with two lag periods is also positive but not significant. This suggests that industrial output agglomeration has a lag effect on regional carbon emissions and that this lag effect is significant for the one lag period. The lag effect is manifested by the aggravation of regional carbon emissions and increased environmental pollution. But over time, the lag effect of industrial output agglomeration on carbon emissions becomes not significant.

Table 3 The impact of Industrial agglomeration on carbon emissions

Variable	Coefficient	Coefficient	Coefficient	Coefficient
lnIA	-0.2580**			
lnIA$_{-1}$	0.2306**			
lnIA$_{-2}$	0.0027			
lnLA		1.1305 ***		
lnLA$_{-1}$		-0.0533		
lnLA$_{-2}$		-0.0468		
lnCA			0.0586	
lnCA$_{-1}$			0.0133	
lnCA$_{-2}$			0.0879	
lnTA				0.1453*
lnTA$_{-1}$				-0.0004*
lnTA$_{-2}$				-0.0320*
lnEE	0.4055***	1.1265 ***	0.3573***	0.6147***
lnGDP	0.2780***	0.0523	0.2417***	0.7808***
lnFDI	-0.0196*	-0.0064	-0.0270**	-0.3056***
lnIS	0.3675***	0.0175	0.0194	1.6919***
ρ	0.2560***	0.1010**	0.0910*	-0.0070*
Individual effect	control	control	control	control
Time effect	control	control	control	control
Adjusted R^2	0.8618	0.5830	0.2948	0.5543
Log likelihood	326.7002	478.6130	343.0981	-362.9258

Note: Significance: * P<0.1, ** P<0.05, *** P<0.01

For industrial labor agglomeration, but its lagging impact is negative and not significant. As shown in Table 3, the coefficient for industrial labor agglomeration is positive and significant at the 1% level, indicating that industrial labor agglomeration has increased regional carbon emissions. The results suggest industrial labor agglomerations exhibit negative externalities on carbon emission levels, which is consistent with the research conclusions of Zhang and Wang (2014), Ya and Meng (2019), Zhang et al. (2019), Dong et al. (2020), Ding et al. (2020), and Lu et al. (2021). The concentration of industrial labor is not conducive to achieving regional carbon control targets. China is still dominated by labor-intensive industries, where the proportion of low-end industrial workers remains relatively large and concentrated(Dong et al. 2020). In comparison, capital and technology-intensive industries are less concentrated where the proportion of high-end industrial workers is lower (Ding et al. 2020). The coefficients for industrial labor agglomeration with one and two lag periods are both negative and not significant. This suggests that the lag effect of industrial labor agglomeration is not significant and that its effect on carbon levels will not considerably change over time.

For industrial capital agglomeration, its impact on carbon emissions was found to be not significant. In Table 3, the coefficients for industrial capital agglomeration and two lagging periods are positive and non-significant. The impact of industrial capital agglomeration on regional carbon emissions is not significant mainly because, in China, the degree of industrial capital agglomeration is far lower than labor. The agglomeration of industrial capital is inefficient and has limited direct effect on the regional environment(Zhao et al. 2020). Industrial capital is often reflected in the introduction of technology and equipment, affecting regional carbon levels and ultimately resulting in labor, technology, and output concentrations of the regional industrial agglomeration.

Industrial technology agglomeration was found to intensify regional carbon emissions and cause environmental degradation. However, its lag effect is positive, which suggests that, over time, regional carbon emissions are effectively suppressed. As shown in Table 3, the coefficient for industrial technology agglomeration is 0.1453, significant at the 10% level, which indicates that it increases prevailing regional carbon emissions. Industrial technology agglomeration normally does not immediately produce innovation effects and is mainly manifested as a cost effect, resulting in environmental degradation. The estimated coefficients for the one and two lagging periods are negative and statistically significant. This indicates that industrial technology agglomeration has a positive lag effect on carbon emissions. Comparing the significance level of the coefficients, we found that the one with the two lagging periods has higher significance level than the one with only one lagging period. This suggests that over time, industrial technology agglomeration shifts from increasing carbon emission towards reducing carbon levels. Industrial technology agglomeration gradually exerts an innovative compensation effect, which can be conducive to improving the regional environment and help control carbon emissions (Pei et al. 2020). This finding supports the conclusions of Chen et al. (2020) and Pei et al. (2020) to a certain extent. Technology agglomeration may cause a transitory increase in environmental pollution but would later result in a positive environmental effect and reduce carbon emissions in the long-term.

The spatial correlation coefficient ρ for carbon emissions is significant at the 10% level in all four models. This suggests that carbon emissions have significant spatial spillover effects, where the region's carbon emissions affect the carbon levels of its surrounding areas. The ρ values are 0.2560, 0.1010, 0.0910, and -0.0070, which indicates that carbon emissions' spatial correlation is dominated by positive autocorrelation. Regional carbon emissions show high agglomeration in high-carbon emission regions and low agglomeration in low-carbon emission regions. The spatial correlation coefficient ρ is significant, highlighting the importance of considering the spatial dimensions in these types of research. The results also suggest that the region's carbon emission level is affected not only by its own industrial agglomeration but also by the level of agglomeration in the surrounding areas.

In terms of control variables, energy consumption, economic development level, and industrial structure were found to significantly intensify regional carbon emissions. The coefficients for these three parameters are all positive, although not significant. The coefficient for FDI (see Table 4) is positive in all models, although two are not significant. These findings suggest that the introduction of FDI plays a positive role in improving the environment and controlling regional carbon emissions.

In general, industrial output agglomeration plays a significant role in restraining the prevailing regional carbon emissions and is conducive to regional environmental governance. In line with the goals and policies of the Chinese government, the development of more industrial clusters and industrial parks can be used to promote economic development and help improve the environment. However, industrial labor and technology agglomerations exert negative external effects, leading to increased regional carbon emission levels. Industrial output and technology agglomerations have significant lag effects, while the direct and lag effects of industrial capital agglomeration on carbon emissions are not significant.

3.3 The impact of industrial agglomeration on carbon emissions from the perspective of regional differences

To further explore the regional differences in the impact of environmental regulations on carbon emissions, we divided the research area into three regions: eastern, central, and western, as shown in Figure 5[1]:

[1] Liaoning, Shanghai, Beijing, Fujian, Tianjin, Zhejiang, Hebei, Jiangsu, Guangdong, Shandong, Hainan and Guangxi provinces are located in the eastern region. Hubei, Shanxi, Heilongjiang, Inner Mongolia, Henan, Anhui, Jilin, Jiangxi and Hunan provinces are located in the central region. Sichuan, Guizhou, Ningxia, Gansu, Yunnan, Shanxi, Chongqing, Xinjiang, and Qinghai provinces are located in the western region.

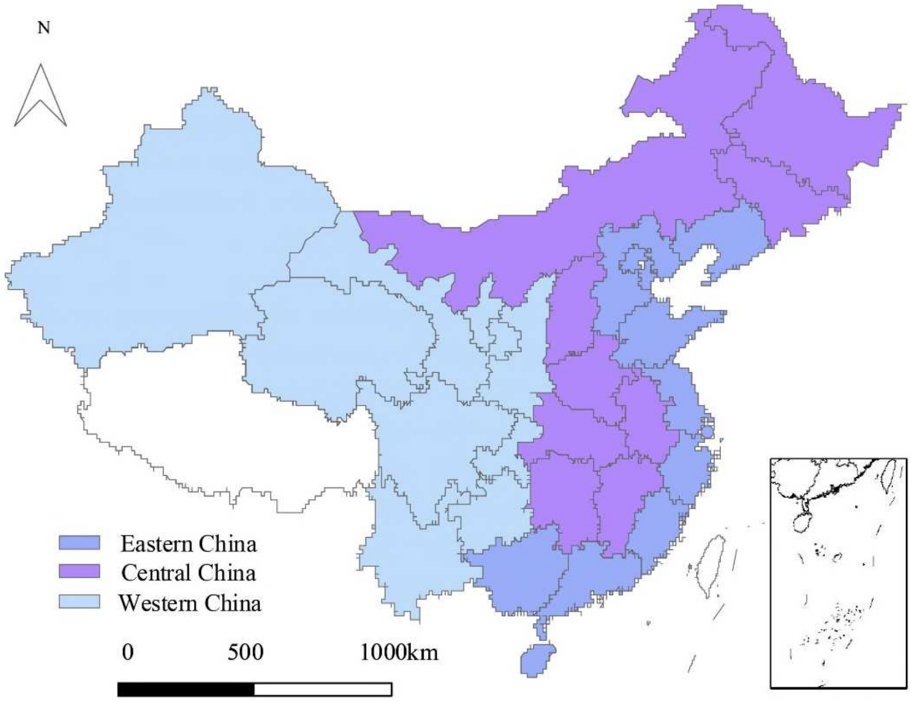

Fig. 5. The eastern, central, and western regions in China

3.3.1 Industrial output agglomeration affects regional differences in carbon emissions

The coefficient for industrial output agglomeration in the eastern and central regions is negative and significant at the 1% level, indicating that industrial output agglomeration reduces carbon emissions in these regions. This result confirms the robustness of the national panel data regression results in Table 4. For the western region, the industrial output agglomeration coefficient is significant and positive, suggesting that industrial output agglomeration increases regional carbon emissions in China’s western provinces. The main reason for this difference is the regional distribution of industries in China. Due to the country’s regional development policy and partly due to its war preparation strategies in the early days of the founding of the People’s Republic of China, industries were roughly evenly dispersed throughout the country. But after major economic reforms and opening up, the distribution of industries began to show gradual agglomeration in the eastern and central regions, particularly in the southeast coastal areas (Yi and Zhou 2020). In addition, the lag effect of industrial output agglomeration significantly increased carbon emissions in the eastern and western regions, while the effect is not significant for the central region.

Table 4 The impact of Industrial output agglomeration on carbon emissions

Variable	Eastern region	Central region	Western region
	Coefficient	Coefficient	Coefficient
lnOA	-0.8629***	-0.6582***	1.1047***
$lnOA_{-1}$	0.4426***	0.1309	0.3501**
$lnOA_{-2}$	-0.0320	0.0160	-0.1648
lnEE	-0.0393	0.6979***	0.4894***
lngdp	1.0625***	0.8132***	-1.0200***
lnFDI	-0.0745**	0.0625***	0.0174
lnIS	0.9544***	0.7092***	-0.9638***
ρ	0.4527***	-0.2361***	0.0880**
Individual effect	control	control	control
Time effect	control	control	control
Adjusted R^2	0.8409	0.9291	0.9151
log-likelihood	124.0199	153.8160	115.6660

Note: Significance: * P<0.1, ** P<0.05, *** P<0.01

3.3.2 Industrial labor agglomeration affects regional differences in carbon emissions

Table 5 reports the results of the impact of industrial labor agglomeration on carbon emissions. The coefficients for industrial labor agglomeration in the eastern, central, and western regions are 1.133, 1.1186, and 0.9173, respectively, significant at the 1% level. The results suggest that for every 1% increase in industrial labor agglomeration, carbon emissions increase by 1.133%, 1.1186%, and 0.9173%, consistent with the national results. In all three regions, industrial labor agglomeration increased environmental pollution. One possible reason is that government-initiated industrial parks and employment-oriented industrial agglomerations are largely dominated by low-end labor. This kind of labor agglomeration is unable to attract high-level talents and cannot produce the corresponding "technical effect", which is not conducive to the innovation of clean, energy-saving, and emission-reducing technologies (Yao et al. 2020). For example, in the eastern coastal areas, the labor sector in many industrial clusters is composed mainly of unskilled migrant workers. These clusters are unable to achieve knowledge innovation and talent agglomeration effects. The influx of migrant workers to the eastern and central industrial agglomeration regions may also lead to increased energy and raw material consumption, more waste discharges (e.g., household garbage), and higher environmental pollution. The industrial labor agglomeration with two lag periods has a significant control effect for the central region, while not significant for the other regions.

Table5. The impact of industrial labor agglomeration on carbon emissions

Variable	Eastern region	Central region	Western region
	Coefficient	Coefficient	Coefficient
lnLA	1.1333***	1.1186***	0.9173***
$lnLA_{-1}$	0.0104	0.0155	-0.0131
$lnLA_{-2}$	-0.0015	-0.0445***	0.0005
lnEE	0.9086***	1.0686***	1.1923***
lngdp	0.0352	0.0688	-0.0459
lnFDI	-0.1108***	-0.0151	0.0250**
lnIS	0.0956	-0.0055	0.1200*
ρ	0.1523***	-0.2361***	-0.0650**
Individual effect	control	control	control
Time effect	control	control	control
Adjusted R^2	0.8876	0.9629	0.9502
log-likelihood	159.4285	143.3400	156.4740

Note: Significance: * P<0.1, ** P<0.05, *** P<0.01

3.3.3. Industrial capital agglomeration affects regional differences in carbon emissions

While industrial capital agglomeration was not significant in the eastern and central regions, it significantly increased regional carbon emissions in the western region (see table 6). This is probably because of China's current industrial agglomerations having many labor-intensive, low-capital, and low-technology industries. In recent years, the Chinese government has initiated measures focused on developing the western region. This western development strategy is mainly characterized by infusing more government funds and economic agglomerations from cross-administrative economic belts (Chen et al. 2018). While this type of government-led industrial agglomeration has capital agglomeration characteristics, the western region's economic development has been comparatively low (Chen et al.

2018). To promote industrial development and support industrial agglomeration, many infrastructure projects, such as roads and railways, would have to be undertaken, which may cause greater environmental damage (Ya and Meng 2019). The results also show that the lagged impact of industrial capital agglomeration on carbon emissions is not significant in the three regions. The effect of capital agglomeration on regional carbon emissions is mainly manifested in the immediate term but is not significant in the long-term.

Table 6. The impact of industrial capital agglomeration on carbon emissions

Variable	Eastern region	Central region	Western region
	Coefficient	Coefficient	Coefficient
lnCA	-0.0341	0.2230	0.6908***
$lnCA_{-1}$	-0.2386	-0.1346	-0.4252
$lnCA_{-2}$	0.2095	0.1266	0.0938
lnEE	-0.1228	0.7029***	0.4876***
lngdp	0.6861***	0.0524	-0.0932
lnFDI	-0.1150***	0.0610**	0.0255*
lnIS	0.5190***	0.0661	0.1325
ρ	0.2367***	-0.2361***	0.1570**
Individual effect	control	control	control
Time effect	control	control	control
Adjusted R^2	0.8233	0.9299	0.9074
log-likelihood	113.2972	124.7800	107.3165

Note: Significance: * P<0.1, ** P<0.05, *** P<0.01

3.3.4 Industrial technology agglomeration affects regional differences in carbon emissions

The estimated coefficients of industrial technology agglomeration for the eastern, central, and western regions are 0.5030, 0.3902, and 0.2693(see table 7). The effect is significant for the eastern and western regions but not significant in the central region. The findings suggest industrial technology agglomeration has not exerted its technical effects and has not achieved technological innovation and technological diffusion. One possible reason for this is that even with industrial agglomeration, the level of independent R&D and technological innovation remains low (Ya and Meng 2019). Advanced, high-end, low-carbon technologies are mainly obtained through imports, and the current industrial clusters cannot achieve technological innovation and technological diffusion (Han 2020). Technology agglomeration is mainly manifested as a cost effect, and it is difficult to compensate for the innovation effect. In terms of lag effects, the second-stage industrial technological innovation significantly reduced carbon levels only in the eastern region and was not significant for the other two regions.

Table 7. The impact of industrial technology agglomeration on carbon emissions

Variable	Eastern region	Central region	Western region
	Coefficient	Coefficient	Coefficient
lnTA	0.5030***	0.3902	0.2693***
$lnTA_{-1}$	0.0170	-0.1384	0.0032
$lnTA_{-2}$	-0.3225***	-0.1363	0.0230
lnEE	0.0314	1.1747***	0.4719***
lngdp	0.3403***	-1.8953***	-0.8585***
lnFDI	-0.1434***	0.1877***	0.1126***
lnIS	0.3656***	1.5252***	-0.3264
ρ	0.3456***	-0.2361***	-0.9999***
Individual effect	control	control	control
Time effect	control	control	control
Adjusted R^2	0.8459	0.6488	0.5422
log-likelihood	127.2830	113.8900	-41.4597

Note: Significance: * P<0.1, ** P<0.05, *** P<0.01

4 Discussion

In general, industrial agglomeration was able to curb regional carbon emissions and has improved the regional environment. As shown in Table 3 and Figure 6, the current industrial output agglomeration has significant and negative correlations with carbon emissions, which means it is able to lower carbon emissions. Industrial output agglomeration is the concentrated expression of result-oriented industrial agglomeration and may result from either industrial labor agglomeration, industrial capital agglomeration, industrial technology agglomeration, or the combination of the three. The original intention of China's industrial agglomeration, which is guided mainly by market forces and site determination, is based largely on the principle of efficiency. A certain degree of industrial agglomeration realizes the connection between enterprises and local comparative advantages, which can effectively stimulate agglomeration effects, promote economic development, and reduce environmental pollution (Han and Li 2019).

In China, many industrial agglomerations are based on market-driven industrial configuration, which selects suitable industries and promotes industrial agglomeration using market rules and efficiency principles to form agglomeration advantages (Lin et al. 2019). At the same time, in the process of industry selection and layout, the locational advantages of particular regions can be reflected. These advantages include not only comparative advantages in the traditional sense but also spatial externalities determined by specific site conditions. Through market-oriented industrial agglomeration reflecting regional advantages, the problem of industrial structural convergence can be resolved, and the agglomeration effect can be fully utilized, which is a win-win for economic development and environmental protection(Lin et al. 2019).

Industrial agglomeration reduces carbon emissions as a whole(Becker et al. 2020). Although in the short-term, achieving zero carbon emissions or reaching carbon neutrality may not be possible by reducing energy consumption or using renewable energy. However, with the shift towards low-carbon technologies and clean energy, industrial agglomeration can become an important force in promoting carbon neutrality(Sanjuán et al. 2020).

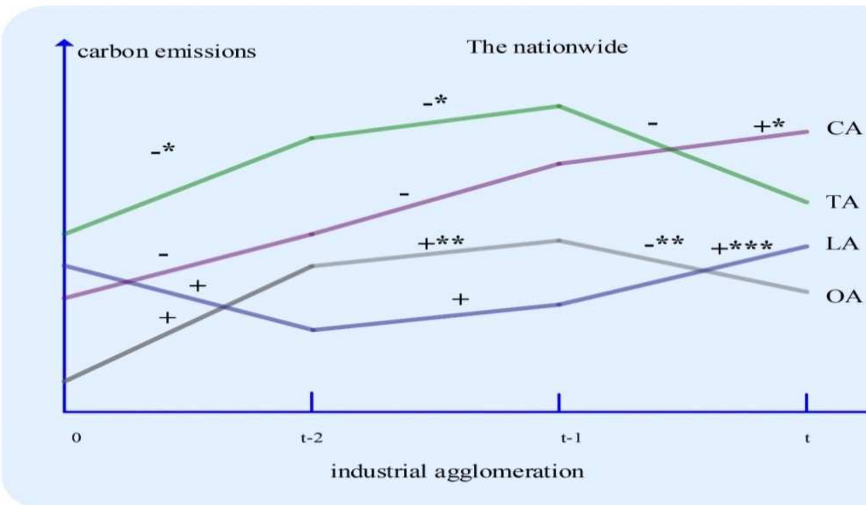

Fig. 6. Schematic diagram of the impact of industrial agglomeration on carbon emissions

Note: + and - represent the sign direction of the estimated coefficient, * represents the significance level.

For different indicators, industrial agglomeration has varying effects on regional carbon emissions. Industrial labor and technology agglomerations significantly increased regional carbon emissions. In China, in order to achieve economic development and maximize fiscal incentives, many local governments actively encourage foreign companies to set up industries in clusters within their jurisdictions (Yang 2017). These agglomerations initiated by local governments promote rapid economic growth in the short term. However, most of these industrial clusters are unable to produce agglomeration effects because they did not fully adhere to prevailing market forces (Guo et al. 2020). Instead, these industrial agglomerations are accompanied by an accelerated rise in urban labor, resulting in the expansion of public infrastructure and intensified urban utilization, which consequently leads to environmental damage and higher pollution levels. Moreover, government-initiated industrial agglomerations are not always consistent with the local and regional comparative advantages (Chen et al. 2020). This, in turn, often leads to low technological innovation and poor technological agglomeration and instead yields negative environmental externalities. In the short term, industrial labor agglomeration and technology agglomeration are not conducive to zero carbon emissions and carbon neutrality.

The effect of capital agglomeration on carbon emissions is not significant. In the agglomeration zone, capital agglomeration is conducive to the sharing of production materials and equipment, which can effectively reduce energy consumption(Zhao et al. 2020)(Zhao et al. 2020)(Zhao et al. 2020)(Zhao et al., 2020). On the other hand, capital agglomeration can help attract highly skilled talents and encourage competition. However, in China, although there is a certain level of resource sharing in industrial agglomeration zones, the use of capital as a core element of enterprise development may not necessarily promote entrepreneurial cooperation (He et al. 2017). This means that capital agglomeration effect cannot be achieved in industrial clusters and that energy conservation cannot be effectively reduced. This also shows that industrial capital agglomeration cannot be the main path to lower enterprise energy consumption and achieve carbon neutrality.

Industrial output and technology agglomerations have significant lag effects, while industrial labor and capital agglomerations do not. The industrial output agglomeration with one lag period significantly aggravated regional carbon emissions, while output with two lag period had a positive but not significant impact. This suggests that the lag effect of industrial output agglomeration increases regional environmental pollution. While industrial agglomeration promotes optimal resource allocation, it can also generate employment demand, leading to urban population growth (Li et al. 2017). The accelerated rise in urban population will lead to higher demands for public facilities and housing and more urban land expansion, consequently increasing regional carbon emissions (Lin et al. 2019).

The lag effect of industrial technology agglomeration helps reduce carbon emissions. While industrial technology agglomeration increased regional carbon emissions in the immediate term, industrial technology agglomeration in both phase 1 and phase 2 lag periods resulted in significantly lower carbon emissions. This shift in the impact of industrial technology agglomeration can be explained by several reasons. First, industrial technology agglomeration is conducive to the imitation and innovation of knowledge and technology (Xu and Liu 2018). Especially in the agglomeration areas, new technologies are often quickly learned and imitated by other companies, which are further improved through innovation(Ding et al. 2020). The proliferation of technological innovation spread in the agglomeration area and ultimately increases enterprises' overall technological innovation level

(Zhang et al. 2019). Over time, technological innovation promotes research and development of low-carbon technology, improves production efficiency, and supports energy conservation. Second, compared to the dispersed spatial pattern, agglomeration is more conducive to the dissemination and diffusion of new knowledge and technologies. Agglomeration improves production efficiency, resulting in energy conservation and emission reduction effects (Pei et al. 2020). Industrial technology agglomeration promotes the sharing of regional information, technology, talents, policies, and resources, which can enhance regional innovation capabilities and competitive advantages (Huang et al. 2019). Industrial technology agglomerations would eventually innovate towards low-carbon technology, become more energy-efficient, and reduce their carbon emissions. Technological innovation is key to low-carbon technologies and the driving force for enterprises to achieve energy conservation and emission reduction(Finnerty et al. 2018). Although technological innovation cannot reduce carbon emissions in the short term, its hysteresis effect is significant. Industrial technology agglomeration can promote the transformation of enterprises towards low-carbon technologies in the long term, reduce energy consumption, and achieve carbon neutrality goals.

Industrial labor and capital agglomerations do not exhibit statistically significant lag effects. The effects of industrial labor and capital agglomerations on carbon emissions were not significant for both lag periods. The sharing of labor in industrial agglomerations can improve labor productivity and resource use efficiency, thereby promoting energy conservation and pollution reduction (Finnerty et al. 2018). Likewise, the sharing of labor is conducive to developing professional talents, enhancing enterprises' innovation capabilities, and reducing energy consumption under established output constraints. The empirical results run counter to the purpose of industrial labor agglomeration, mainly because China’s industrial agglomerations are still dominated by labor-intensive industries with relatively large proportions of low-end industrial practitioners. This leads to low levels of labor sharing in industrial agglomerations and achieves minimal talent sharing advantages. Also, the accumulation of capital in the agglomeration zone is conducive to more unified procurement and recycling of materials and reducing energy usage, which can help conserve energy conservation and reduce carbon emissions (Li et al. 2019). In China, industrial agglomerations are dominated by low-end labor enterprises, making it difficult to realize industrial labor sharing and capital sharing and improbable to exert agglomeration effect.

We found significant regional differences in how industrial agglomeration affects carbon emission levels (see Figure 6). The industrial output agglomeration in the eastern and central regions has a significant carbon mitigation effect, while in the western region, agglomeration exacerbates regional carbon emissions. In recent years, with the rapid industrial advancement and structural reforms in eastern and central China, the economy and the environment have had a relatively good coordinated development(Yao et al. 2020). This development of industrial agglomerations yielded a win-win situation for both economic growth and environmental protection. However, since the western region is still in the initial stage of industrialization, its development model still capitalizes on industrial agglomeration primarily to achieve economic growth, even at the expense of the environment.

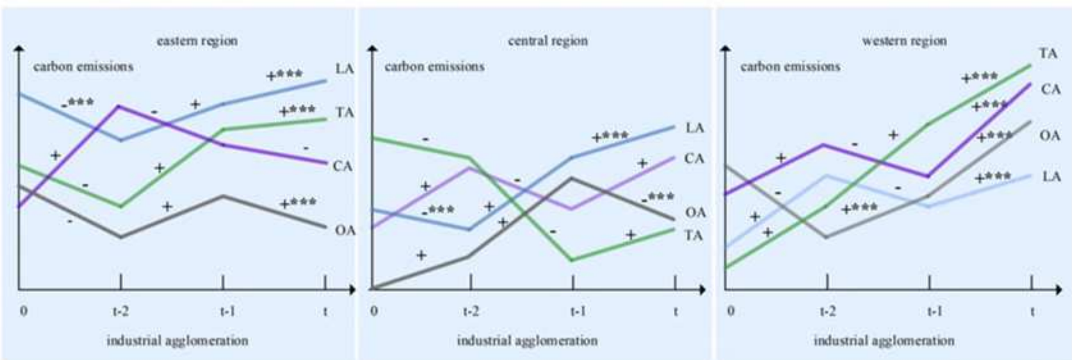

Fig.7. Industrial agglomeration affects regional differences in carbon emissions

Industrial labor and technology agglomerations were shown to aggravate regional carbon emissions in all three regions. China’s industrial agglomerations are still heavily labor-intensive, and many are considered low-end labor agglomerations (Dong et al. 2020). The agglomeration of low-end labor forces makes it difficult to realize labor sharing and knowledge sharing in industrial parks, and thus cannot exert talent accumulation effect. On the other hand, the accumulation of low-end labor will increase the consumption of resources and energy in the industrial park and increase environmental pollution. The accumulation of industrial technology in the three regions has increased carbon emissions, which reflects the cost effect of industrial technology agglomeration. The main reason is that a long period is needed for industrial technology agglomeration to play the compensation innovation effect and exhibit substantial carbon control effects.

Industrial capital agglomeration was to have no significant impact on regional carbon emissions in the eastern and central regions, while in the western regions, it significantly increased emissions. In recent years, the Chinese government has implemented the Western Development Program to vigorously promote the economic development of the western region. The plan uses government funding to construct industrial belts and industrial parks as the main method. Several industrial parks oriented by government policies have been constructed in the western region. The construction of many industrial parks would require extensive use of steel and cement and destroy vegetated areas, resulting in increased environmental pollution. Due to differences in industrial agglomeration characteristics, economic development levels, and regional advantages, the impact of industrial agglomeration on carbon emissions can significantly vary. These variations can lead to considerable differences in the speed and method of achieving carbon neutrality goals in various regions.

5 Conclusions

This study expanded the output density theoretical model of Ciccone and Hall and constructed a theoretical model of the relationship between industrial agglomeration and carbon emissions. Using data from 30 provinces in China from 2002 to 2018, the theoretical model was verified using spatial measurement methods. The main findings are as follows:

(1) Industrial labor and technological agglomerations increase regional carbon emissions, industrial output agglomeration reduces emissions, and industrial capital agglomeration has no significant effect on carbon emissions in the immediate term. This suggests that industrial labor and technological agglomerations have negative environmental externalities, while industrial output agglomeration has mitigation effects on regional carbon emissions.

(2) In terms of lag effects, industrial output and technology agglomerations exhibit significant delays in their effect on carbon emission levels. Industrial output agglomeration significantly reduces carbon emissions in the immediate term but shifts towards increasing regional environmental pollution in the long term. In contrast, industrial technology agglomeration aggravates regional emissions in the immediate term, but over time, its effect becomes positive, reducing carbon emissions significantly.

(3) There are significant regional differences in the impact of industrial output and capital agglomerations on regional carbon emissions, while industrial labor and technological agglomerations have no significant regional differences. Industrial output agglomeration in the eastern and central regions has a significant carbon control effect, while it exacerbates regional carbon emissions in the western region. Industrial capital

agglomeration in the eastern and central regions has no significant impact on carbon emissions, while it significantly increased regional carbon emissions in the western region.

Based on the above research results, this study proposes the following policy recommendations:

(1) The government should pay attention to the relationship between industrial agglomeration, economic development, and carbon neutrality in developing new industrial zones. Increased industrial agglomeration can facilitate more effective energy and resource consumption and encourage new technologies,which is an important way to achieve carbon neutrality. However, industrial labor and technological agglomerations aggravate regional carbon emissions, resulting in negative environmental effects. The government should consider industrial structural reforms and management policy modifications towards more coordinated economic development and carbon neutrality, particularly concerning industrial agglomerations.

(2) In carbon emission governance, coordinated strategies and joint governance mechanisms should be established. This study shows that carbon emissions have a significant spatial spillover effect, which means that a particular region's carbon levels affect its neighboring areas. In China, there are clear delineations in management and governance between administrative regions, which may cause substantial gaps in environmental pollution control and management. Since carbon emissions have strong spatial characteristics, intra-regional coordination strategies and collaboration must be established to jointly plan the layout of industrial clusters and implement environmental governance.

(3) For carbon emission control, the differences between regions should be considered, and different regions have different ways to achieve carbon neutrality goals. In China, the eastern

region is relatively developed and has significant industrial agglomeration characteristics. The central and western regions are comparatively less economically developed, and the agglomeration effect of their industrial sector is not as pronounced. Different regions have varying industrial structures and distinct differences in industrial agglomeration methods. Such regional differences result in industrial agglomerations having heterogeneous effects on carbon emissions. These regional and local differences have to be further explored and considered, particularly in developing policies and strategies on industrial agglomerations.

(4) Companies should fully measure carbon emissions, and use industrial energy conservation and emission reduction as the main method to achieve zero carbon emissions and carbon neutrality. The transformation of the industry to low-carbon and the realization of industrial upgrading are the foundation of the decarbonization of the regional economy.

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Availability of data and materials

The [1126data.xlsx] data used to support the findings of this study have been deposited in the [https://pan.baidu.com/s/1T4UTNRmreyuLGkzzwAyQqQ (password: afrq)].

Competing interests

The authors declare no conflict of interest.

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Author Contributions

Yuanhua Yang conceived the study idea and designed the research framework, wrote the initial manuscript draft. Zhongwen Peng and Dengli Tang collected and performed the data analyses and made a comprehensive English revision.

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