Applied Spatial Analysis and Policy
https://doi.org/10.1007/s12061-022-09470-2

Spatial Impact of Industrial Agglomeration and Environmental Regulation on Environmental Pollution—Evidence from Pollution-Intensive Industries in China

Zheng-Xia He[1] · Chang-Shuai Cao[2] · Jian-Ming Wang[3]

Received: 20 October 2021 / Accepted: 16 June 2022

Abstract
In the context of China's efforts to achieve green economic development and adjust the spatial layout of industries, this article focuses on pollution-intensive industries. Based on the panel data of 30 Chinese provinces from 2003 to 2018, the spatial locational characteristics and development directions of pollution-intensive industrial agglomeration and environmental pollution are revealed. The effects of environmental regulations and polluting industrial agglomeration on ecological pollution are explored by constructing a dynamic spatial panel Durbin model. The research found that: ①Both the concentration of pollution-intensive industries and environmental pollution tend to shift from the east to the central and western parts of China; ②Environmental regulations have a significant inhibitory effect on environmental pollution, and there is a negative spatial spillover effect; ③Pollution Industrial agglomeration and ecological pollution have an inverted "U"-shaped nonlinear relationship, and there is a positive spatial spillover effect. The research conclusions of this paper provide a theoretical basis for optimizing the spatial layout of pollution-intensive industries, alleviating environmental problems, and realizing the development of the green economy.

Keywords Environmental regulation · Pollution-intensive industries · Spatial Durbin model · Environmental pollution · Spatial spillover effect

Introduction

Since the reform and opening-up, China's urbanization process has promoted economic prosperity and development. At the same time, it has caused a series of environmental problems, posing a significant threat to ecological governance (Wang

✉ Chang-Shuai Cao
caochangshuai@yeah.net

Extended author information available on the last page of the article

et al., 2012). In pursuing high-quality economic development, environmental pollution problems are becoming increasingly prominent and need to be further curbed and improved (Whittet et al., 2016; Zeng et al., 2019). Under the dual pressure of economy and pollution, national ministries and provincial regions have introduced related policies to actively promote the adjustment and optimization of the layout of polluting industries. For example, 《Key Industrial Productivity Layout and Adjustment Plan》 developed and implemented in China states that clusters of pollution-intensive enterprises such as coal, electric power, and petrochemicals should be promoted. "The 13th Five-Year Plan also continues to promote green development, optimize traditional manufacturing industries, and focus on improving the ecological environment.

Environmental regulation has been widely recognized and applied as an effective tool and powerful instrument to solve environmental pollution problems (Porter & Van der Linde, 1995). Resource and ecological constraints are essential drivers for transferring pollution-intensive industries and robust measures to reduce regional pollutant and waste emissions (Willy et al., 2019). However, spatial agglomeration of environmental pollution further increases the difficulty of government regulation because regions possess specific spatial differences in terms of economic level and resource endowment (Chen et al., 2018). At the same time, the state-guided pollution-intensive industrial agglomeration has the most apparent spatial geographic characteristics as a currently prevalent economic agglomeration activity. In the framework of new economic geography, the industrial agglomeration has positive external effects, i.e., scale impact, technological innovation effect, etc., and adverse external effects, i.e., "crowding" effect of excessive resource consumption and emission increase etc. (Elahi et al., 2019). In pursuing green economic development, what is the relationship between environmental regulation, pollution-intensive industrial agglomeration, and environmental pollution from a spatial perspective? What kind of locational characteristics and development direction does pollution-intensive industrial development possess? How can spatial linkages and spillover effects play a positive role in the future? The solution to these questions is of great practical significance to China's green and sustainable development. In the context of green development transition, it is important to investigate the influence of environmental regulation and polluting industry clustering on environmental pollution, grasp the environmental regulation policy, polluting industry and the evolutionary law of environmental pollution, and then plan the sustainable development of the region. Although existing studies have empirically investigated the influence of both on environmental pollution, studies exploring environmental regulation and pollution-based industrial agglomeration on environmental pollution from the perspective of new structural economics are rare. The transfer of environmental pollution is not a mere spatial transfer, and the spatial correlation between regions needs to be considered when environmental regulation policies and the impact of polluting industrial agglomeration activities so that more accurate research results can be obtained and more scientific empirical evidence can be provided for environmental governance.

While most existing studies focus on manufacturing or industry as the primary research object, this paper further investigates pollution-intensive enterprises with more significant environmental impacts (Zhou & Feng, 2017). From a spatial and temporal perspective, data from 30 Chinese provinces (excluding Tibet, Hong Kong, Macao, and Taiwan) from 2003 to 2018 are selected to establish a spatial econometric model, which firstly points out the migration status of the center of gravity of environmental pollution and pollution-intensive industrial agglomeration in China and considers the environmental effects of environmental regulation and pollution-intensive industrial agglomeration. On this basis, the non-linear relationship between the agglomeration of polluting industries and environmental pollution is explored. Finally, from the perspective of energy conservation and emission reduction, we provide a theoretical basis for the rational layout of pollution-intensive industries and propose policy recommendations to alleviate environmental problems and green economic transformation. Compared with the existing studies, the main contributions and possible innovations of this paper are as follows: (i) The spatial shift of the center of gravity of pollution-intensive industrial agglomeration and environmental pollution was pointed out for the first time; (ii) This paper explores the impact of governmental environmental regulations on pollution in spatially adjacent areas based on the spillover characteristics of environmental pollution and the undesirable phenomena of "bottom-up competition" and "free-riding" of governmental environmental regulations, which can provide theoretical references for the current environmental regulation policy formulation in various provinces of China; (iii) Based on the identification of pollution-intensive industries, the non-linear relationship between industrial agglomeration and environmental pollution is explained from the perspective of spatial spillover, which enriches the theory of industrial agglomeration.

Literature Review

Study on the Relationship between Environmental Regulation and Environmental Pollution

As an essential tool and instrument to mitigate environmental problems, environmental regulation has been widely studied and applied in various countries or regions (Zhao & Sun, 2016). However, due to the different selection of indicators and research samples, academics have different views on the relationship between environmental regulation and environmental pollution, and no unified conclusion has been formed yet. Hence, the use of comprehensive indicator weights to achieve a unified measurement of the intensity of environmental regulation is the focus of environmental regulation research. From the perspective of pollution emissions, (Porter, 1996) argues that stronger environmental regulation can reduce environmental pollution while promoting more innovative activities by firms (Porter, 1996). The production benefits brought by technological innovation can also effectively offset the cost of environmental protection. (Dasgupta et al., 2001; Christian et al., 2016).

Studies have also shown that environmental regulation can significantly curb ecological pollution. Higher environmental pressures motivate firms to undertake R&D and technological upgrades, and pollutants receive higher overall utilization and treatment rates, thus reducing environmental pollution. (Ambec et al., 2013), taking the U.S. manufacturing industry as an example, it concluded that ecological regulations could improve business efficiency, such as competitiveness, profitability, etc. Also (Zhou & Feng, 2017) showed that environmental regulation could significantly inhibit the expansion of heavy industries and reduce the use of fossil energy, with a significant negative relationship with ecological pollution emissions. (Elgin and Mazhar, 2013) empirically concluded that environmental regulation has a significant inhibitory effect on ecological pollution using more than 100 countries' panel data. In terms of the number of polluting firms, (List et al., 2003) argue that strict environmental regulations have led to a sharp reduction in the number of new small firms that emit a large number of pollutants, which indirectly leads to a reduction in environmental pollution as strict regulatory regimes and measures significantly increase the costs of producers and raise the market entry barriers. At the same time, some studies show that environmental regulations are ineffective in reducing environmental pollution. For example, (Sinn, 2008) proposed the "green paradox," which argues that stringent ecological regulations do not reduce pollutant emissions but rather reduce the efficiency of business operations, which is not conducive to improving environmental quality. Similarly, (Saltari & Travaglini, 2011) and (Leiter et al., 2011) have concluded that strict environmental regulations have a significant disincentive effect on firms and positively contribute to pollution emissions. Some other scholars have concluded that environmental regulation is a threshold effect on environmental pollution, i.e., the uncertainty of the impact of environmental regulation on environmental pollution may be due to differences in the intensity of environmental regulation (Zhao & Sun, 2016).

The main reason for the uncertainty in the relationship between environmental regulation and environmental pollution in the current study is that higher environmental regulation, although beneficial to curb the emission of environmental pollution, increases the operating costs and economic burden of firms, and thus does not have a significant effect on environmental pollution (Dai et al., 2020; Sinn, 2008). We may divide the process of ecological regulation's impact on environmental pollution into long and short terms. In a short time, the government's solid ecological regulation policy measures lead to a rapid increase in the cost of production and operation of enterprises. There is no way to adjust their production methods because the technological upgrading has not yet been completed, which may not effectively improve the pollution emissions of some enterprises due to the dominant "cost" effect (Palmer et al., 1995). However, enterprises are forced to carry out green technology innovation in the long run under high environmental pressure, and the "innovation" effect is much more significant than the "cast" effect. The technology innovation improves production efficiency and pollution treatment rate, reducing pollution emissions. At the same time, behaviors such as learning and learning from the regulatory policies of neighboring provinces will lead to further curbs on pollution at the global level. Based on this, the following hypothesis, H1, is proposed.

H1: Environmental regulation can effectively alleviate the environmental pollution problem in the province and reduce the spatial spillover effect of pollution.

Study on the Relationship between the Agglomeration of Polluting Industries and Environmental Pollution

There are three main views in the existing literature on the impact of industrial agglomeration on environmental pollution as follows: (1) Industrial agglomeration has a negative externality effect on environmental pollution due to the expansion of the scale of industrial agglomeration and the sharp increase in the consumption of energy and resources required, which leads to further deterioration of environmental pollution. Industrial agglomeration further expands population size and wasteful resources, leading to pollution deterioration (Van Doorn and Verhoef, 2008; Wang & Wang, 2019). A quasi-natural experimental study found that there is a tendency for pollutant emissions to increase sharply after the establishment of industrial agglomeration development (Wang & Nie, 2016); (2) industrial agglomeration has a positive externality effect on environmental pollution, which means that industrial agglomeration has a significant energy-saving and emission reduction effect on environmental pollution (Marshall, 1920). Numerous economic theories have explained this effect from multiple perspectives: the economic theory of agglomeration argues that industrial agglomeration in space is conducive to the division of labor and collaboration among enterprises, which promotes the dissemination of technology and knowledge and leads to learning effect spillover; the economic theory of scale argues that industrial agglomeration can bring about scale effects, further increasing the production efficiency of enterprises and improving the innovation environment in the region; the theory of industrial organization argues that industrial agglomeration The industrial organization theory suggests that industrial aggregations, as competitive groups with relative advantages, constitute higher barriers compared to enterprises outside the agglomerations, making it impossible for low-end industrial chains to enter the agglomerations, thus indirectly promoting energy conservation and emission reduction. Studies have shown that industrial agglomeration's energy-saving and emission reduction effects and scale effects through knowledge or technology spillover have significant positive externalities on the environment (Ehrenfeld, 2003; Krugman, 1998). (Karkalakos, 2010; Baomin et al., 2012) suggested that industrial agglomeration can generate positive externalities because of economic scale growth and technological progress. (Copeland & Taylor, 2004) argued that industrial agglomeration could bring about scale effects in pollution control, implying that industrial agglomeration brings about higher waste utilization and a total treatment rate of pollution. (3) There is an inverted "U" curve relationship between industrial agglomeration and environmental pollution, i.e., the Kuznets curve. (Jalil & Feridun, 2011), by introducing the squared term of agglomeration level, industrial agglomeration can promote the emission of pollutants, and the emission of pollutants decreases significantly with the increase of agglomeration level. (Feng et al., 2020) studied using spatial measures and concluded that industrial agglomeration and pollution have a relationship of promotion followed by inhibition. China's guided industrial agglomeration has played an important role in energy conservation and emission reduction. For a long time, many enterprises have been laid out in some location-advantaged areas such as the eastern coastal region for agglomeration effects and further cost savings. For example (Pei et al., 2021; Shen & Peng, 2021) found that industrial agglomeration in the Yangtze River Economic Zone significantly improved environmental conditions.

This nonlinear relationship may be that when the negative externality of industrial agglomeration is greater than the positive externality, the crowding effect on resources is greater than the agglomeration or scale effect, thus exacerbating the environmental pollution situation. When the negative externality is gradually smaller or much smaller than the positive externality, the agglomeration or scale effect is much larger than the crowding effect. Under the centripetal force, various rich elements will keep pouring into the agglomeration, resulting in the technology and knowledge effect of the agglomeration area being amplified, thus improving environmental pollution. It can be seen that there may be a non-linear relationship between industrial agglomeration and environmental pollution (as shown in Fig. 1).

To sum up, this paper tries to investigate in depth the following two aspects: (i) the use of ArcGIS software to point out the migration of the center of gravity and the spatial distribution of polluting industrial agglomeration and environmental pollution; (ii) the selection of polluting-intensive enterprises with more significant environmental impact, the establishment of a spatial Durbin model to investigate the spatial spillover effect of polluting industrial agglomeration on environmental pollution; (iii) the introduction of the squared term of the level of polluting-intensive industrial agglomeration to explore the nonlinear relationship between the agglomeration of pollution-intensive industries and environmental pollution. This will enrich the connotation of agglomeration economy theory and provide a theoretical basis for the emission reduction effect of industrial agglomeration in China. Based on this, the following hypothesis, H2, is proposed.

H2: Pollution-intensive industrial agglomeration can promote environmental pollution status and has a positive spatial spillover effect. However, with the improvement of the agglomeration level, pollution-intensive industrial agglomeration can effectively suppress ecological pollution, i.e., there is an inverted "U"

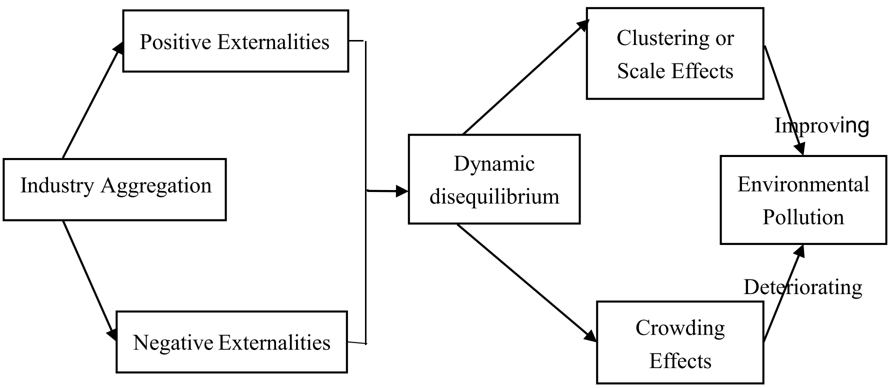

Fig. 1 Non-linear Mechanism of Industrial Agglomeration and Environmental Pollution

curve relationship between pollution-intensive industrial agglomeration and environmental pollution.

Empirical Analysis

Econometric Model Construction

Since environmental pollution is a continuously changing dynamic process, it is essential to consider its time lag. Therefore, the first-order lag term of environmental pollution is included in the model as an explanatory variable. Meanwhile, the theory of ecological Kuznets curve points out that in economic development, the environmental pollution situation will show a changing trend of deterioration before getting initial improvement. Based on this, this study introduces the squared term of pollution-intensive industrial agglomeration level to test whether there is an inverted U-shaped relationship between pollution-intensive industrial agglomeration level and environmental pollution based on the premise of verifying the positive effect of pollution-intensive industrial agglomeration on environmental pollution and to study the ecological regulation, pollution-intensive industrial agglomeration level and environmental pollution in this province and spatially related provinces. In addition, the spatial relationship between environmental regulations, the concentration level of polluting industries, and environmental pollution in this province and spatially related provinces should be studied. To this end, this study employs a dynamic spatial Durbin model for empirical analysis.

$$y_{it} = \tau y_{it-1} + \rho W_{ij} y_{it} + \beta X_{it} + \theta W_{ij} X_{it} + \delta Z_{it} + \varphi W_{ij} Z_{it} + \mu_i + \omega_t + \varepsilon_{it} \tag{1}$$

Eq. i represents each province, t stands for time. y_{it} is the explanatory variable, i.e., the environmental pollution in each province(Pollution).τ reflects the dynamic effect of environmental pollution.y_{it-1} is the lagged term of the explained variable.ρ is the spatial autoregressive coefficient, reflecting a spatial autocorrelation of ecological pollution in different provinces. W_{ij} is the spatial weight matrix. β and δ are the coefficient terms of the core explanatory and control variables, respectively. X_{it} are the core explanatory variables, i.e., environmental regulation (ER), the level of concentration of polluting industries (IA), and its squared term (IA^2). Z_{it} are control variables, including total year-end population (P), per capita wage level (Wage), science and technology inputs (T), and foreign direct investment (FDI) in each province (Open). $W_{ij}X_{it}$、$W_{ij}Z_{it}$ are the spatial lagged terms of the core explanatory variables and control variables, θ、φ are their coefficients, respectively. μ_i is the spatial fixed effect, ω_t is the time fixed effect, ε_{it} is the random disturbance term. When $\theta = \varphi = 0$, the model can be reduced to the SAR model; when $\rho = 0$ and $\theta = \varphi = 0$, the model can be reduced to the SEM model.

Description of Main Variables

① Emissions of environmental pollution. Sulfur dioxide is the main component of air pollution. China is also one of the countries with more sulfur dioxide emissions; therefore, the two leading pollution indicators currently planned to reduce emissions include sulfur dioxide (Zeng et al., 2019). Due to the non-additivity caused by different pollutant units, this paper uses a single pollutant sulfur dioxide emission index to measure environmental pollution emissions according to the proportion of pollutant components and the degree of harm and uses the natural logarithm of total industrial sulfur dioxide emissions in each province as a measure of environmental pollution emissions in view of the availability and completeness of data.

② polluting industrial agglomeration. Different industry agglomeration levels are measured differently, and location entropy is more specialized in measuring the agglomeration level of an industry. Meanwhile, some scholars have also used the spatial Gini coefficient, spatial autocorrelation coefficient, Herfindahl index, etc. However, to measure the level of concentration of pollution-intensive industries in each province, it is not only necessary to eliminate the scale differences among provinces, but also to reflect the specialization advantages and spatial distribution patterns among provinces, and locational entropy is more reasonable (Han et al., 2019; Zheng & Lin, 2018). In this paper, the five industries with the highest emissions in the sectors emitting waste gas pollution, industries emitting wastewater pollution, and industries emitting solid waste (Table 1) will be selected and defined as pollution-intensive industries, of which a total of 10 sectors will be excluded from the same terms (Milani, 2017; Ramanathan et al., 2017). The number of employees in these ten pollution-intensive industries was used as an output indicator to calculate the entropy of the location of pollution-intensive industries, which was calculated as follows.

$$IA_{it} = \frac{m_{it} / M_{it}}{\sum_{i=1}^{30} m_{it} \Big/ \sum_{i=1}^{30} M_{it}} \tag{2}$$

③ Environmental regulation intensity. In this paper, using the entropy weighting method, the indicators of industrial sulfur dioxide removal rate (x_1), industrial soot removal rate (x_2), industrial solid waste comprehensive utilization rate (x_3), industrial wastewater treatment rate (x_4), and domestic waste harmless treatment rate (x_5) are selected to measure the environmental regulation intensity of each province comprehensively. The specific calculation steps are as follows.

(1) Standardization of raw data.

$$x'_{ij} = (x_{ij} - \overline{x}) / s_j \tag{3}$$

Table 1 Pollution-intensive Industry Pollution Ranking

Ranking	Emission of Exhaust Gas Pollution Industry	Discharge of Wastewater Pollution Industry	Burst of Solid Waste Industry
1	Electricity/heat production and supply industry	Coal mining and washing industry	Electricity/heat production and supply industry
2	The ferrous metal smelting and rolling processing industry	Electricity/heat production and supply industry	Ferrous metal mining industry
3	Non-metallic mineral products industry	Chemical raw materials and chemical products manufacturing	Coal mining and washing industry
4	The non-ferrous metal smelting and rolling processing industry	Paper and paper products industry	Non-ferrous metal mining industry
5	Chemical raw materials and chemical products manufacturing	Textile industry	The ferrous metal smelting and rolling processing industry

The original value of the province i and indicator j, x'_{ij} is the standardized indicator value, and $\bar{x}$, s_j are the mean and standard deviation of the eth indicator, respectively.

(2) Isomorphize the indicators and calculate the share of the province i in the indicator $j(p_{ij})$:

$$p_{ij} = Z_{ij} \Big/ \sum_{i=1}^{n} Z_{ij}\,(i = 1, 2, \cdots \mathrm{n}; j = 1, 2, \cdots m) \tag{4}$$

(3) Calculate the entropy value of the indicator j (e_j):

$$e_j = -k \sum_{i=1}^{n} p_{ij} \ln\left(p_{ij}\right), \quad k = 1/\ln(\mathrm{n}), e_j \geq 0 \tag{5}$$

(4) Calculate the coefficient of variation of the indicator j (g_j):

$$g_j = 1 - e_j \tag{6}$$

(5) Normalize the coefficient of variation and calculate the weight of the indicator j (w_j):

$$w_j = g_j \Big/ \sum_{j=1}^{m} g_j,\ (j = 1, 2, \cdots m) \tag{7}$$

(6) Calculate the intensity of environmental regulation in the province $i(ER_i)$:

$$ER_i = \sum_{j=1}^{m} w_j p_{ij} \tag{8}$$

④ In this paper, the total year-end population (P), per capita wage level (Wage), science and technology investment (T), and actual foreign investment utilization (Open) in each province of China are selected as control variables. The total year-end population (P) reflects the population base of the province, and it is generally believed that the larger the population base is, the more environmental pollution is generated and the more the population migrates to surrounding provinces; the per capita wage level (Wage) reflects the per capita purchasing power of residents in each province, and the stronger the per capita purchasing power is, the higher the consumption of resources and the pollution generated; the science and technology investment (T) in each province reflects the technological innovation of each province level, which has a key role in the prevention and treatment of environmental pollution; the actual utilization of foreign capital in each province (Open) reflects the intensity of foreign-funded enterprises in the province, the introduction of foreign capital may cause structural upgrading of polluting industries, and the introduction of resource-consuming enterprises brings environmental pollution along with economic development.

Data Sources and Descriptive Statistics of Variables

The data in this paper are obtained from 《China Statistical Yearbook》 and 《China Environmental Statistical Yearbook》, where the actual utilization of foreign direct investment is converted into units in RMB according to the average exchange rate of each year. In addition, to control for multicollinearity and heteroskedasticity, the natural logarithm form of the control variables is used in the model. The descriptive statistics of the variables are shown in Table 2.

Measurement Results and Analysis

Spatial Autocorrelation Test

Global Moran Index

Before spatial econometric analysis, spatial autocorrelation tests were conducted for environmental pollution and the concentration level of pollution-intensive industries. Spatial autocorrelation is a method to analyze the similarity of attribute values within spatially contiguous or spatially adjacent regions (Tarokh et al., 1998). Validation using the currently accepted global Moran index (Johnson et al., 2005; Xiong et al., 2019).

$$Moran's\,I = \frac{\mathrm{n}}{\sum_{i=1}^{n}(x_i - \overline{x})2}\frac{\sum_{i=1}^{n}\sum_{j=1}^{n}W_{ij}(x_i - \overline{x})(x_j - \overline{x})}{\sum_{i=1}^{n}\sum_{j=1}^{n}W_{ij}} \tag{9}$$

where n is the number of provinces, i and j are the values of the attributes studied in region i and region j, respectively. W_{ij} is the spatial weight coefficient matrix. When $Moran's\,I$ is positive, it indicates that pollution emission or pollution-based industrial agglomeration has a positive spatial correlation, and the more the value of $Moran's\,I$ tends to 1, the stronger the positive correlation of pollution emission;

Table 2 Descriptive Statistics

Variable Description	Variable	Obs	Mean	Std. Dev	Min	Max
Environmental Pollution	Pollution	480	3.737	1.028	-2.257	5.208
Environmental Regulation	ER	480	0.326	0.105	0.09	0.721
Pollution-based industrial agglomeration	IA	480	0.997	0.436	0.183	2.823
Total population	P	480	8.17	0.75	6.28	9.337
Wage	Wage	480	10.489	0.587	9.249	11.89
Science and technology input	T	480	14.096	2.052	6.183	16.932
Actual utilization of foreign capital	Open	480	0.031	0.025	0	0.135

Table 3 Pollution Global Moran Index

Year	Moran's I	Z	P	Year	Moran's I	Z	P
2003	0.280**	1.382	0.046	2011	0.427***	2.484	0.007
2004	0.316**	1.869	0.031	2012	0.426***	2.485	0.006
2005	0.339**	1.992	0.023	2013	0.434***	2.519	0.006
2006	0.342**	2.003	0.023	2014	0.438***	2.546	0.005
2007	0.357**	2.081	0.019	2015	0.450***	2.614	0.004
2008	0.381**	2.214	0.013	2016	0.375**	2.279	0.011
2009	0.403***	2.330	0.010	2017	0.400***	2.346	0.009
2010	0.392**	2.271	0.012	2018	0.395**	2.278	0.011

Table 4 Polluting Industrial Agglomeration Global Moran Index

Year	Moran's I	Z	P	Year	Moran's I	Z	P
2003	0.406***	2.447	0.007	2011	0.187*	2.484	0.090
2004	0.261**	1.662	0.048	2012	0.155*	2.485	0.061
2005	0.210**	1.406	0.080	2013	0.121*	2.519	0.078
2006	0.220*	1.461	0.072	2014	0.174*	2.546	0.091
2007	0.236*	1.534	0.062	2015	0.200*	2.614	0.098
2008	0.222*	1.423	0.077	2016	0.247*	2.279	0.060
2009	0.231*	1.475	0.070	2017	0.249*	2.346	0.053
2010	0.233*	1.478	0.070	2018	0.227*	2.278	0.061

when $Moran's I$ is negative, it indicates that pollution emission or pollution-based industrial agglomeration has a negative spatial correlation, and the more the value of $Moran's I$ tends to -1, the stronger the negative correlation of pollution emission or pollution-based industrial agglomeration; when $Moran's I$ is 0, the stronger the negative correlation of pollution emission or pollution-based industrial agglomeration; when $Moran's I$ is negative, the stronger the negative correlation of pollution emission or pollution-based industrial agglomeration. When $Moran's I$ is negative, it means that there is a negative spatial correlation between pollution emissions or pollution-based industrial agglomeration, and the more the value of $Moran's I$ tends to -1, the stronger the negative correlation between pollution emissions or pollution-based industrial agglomeration. When $Moran's I$ it is 0, it indicates no spatial correlation between polluting emissions or polluting industrial clusters, which are randomly distributed in space (Zhang & Zhang, 2007).

From Table 3, it can be obtained that the global $Moran's I$ indices of the overall environmental pollution level in China from 2003 to 2018 are significant and positive, taking values in the range of 0.280–0.450. The results indicate a significant positive spatial autocorrelation of China's overall environmental pollution level, showing a relatively spatial solid agglomeration pattern. The agglomeration development of pollution-intensive industries in China is easily influenced by resource endowment, labor force level, and scientific and technological inputs, which often lead to a specific spatial autocorrelation or spatial heterogeneity agglomeration of pollution-intensive industries. As shown in Table 4, the global $Moran's\,I$ indices of the agglomeration level of pollution-intensive industries in China are all significantly positive and have a certain spatial autocorrelation. Provinces with higher concentration levels of pollution-intensive sectors tend to be closer to other provinces with higher concentration levels. In addition, the indexes show a specific overall decreasing trend, and the spatial dependence gradually decreases.

Local Moran Index

The local Moran index can test the spatial autocorrelation between the localities with the following equation (Zhang et al., 2018).

$$I_i = \frac{y_i - \overline{y}}{S^2} \sum_{j=1}^{n} W_{ij}(y_i - \overline{y}) \tag{10}$$

$$S^2 = \frac{1}{n} \sum_{i=1}^{n} (y_i - \overline{y})^2, \overline{y} = \frac{1}{n} \sum_{i=1}^{n} y_i \tag{11}$$

In the formula, I_i is the local autocorrelation index, y_i and $\overline{y}$ are attribute values between different provinces, n is the number of provinces, and W_{ij} is the spatial weight coefficient matrix.

From the results of the local spatial correlation test of environmental pollution in 2003 and 2018 shown in Fig. 2, it can be concluded that the local Moran index is 0.168, 0.213, 0.344, and 0.196 in 2003 and 2018, respectively, indicating that environmental pollution and pollution-based industrial agglomeration in China have a strong spatial autocorrelation. We can get that there is a trend that the regions showing the "high-high" agglomeration pattern are shifting from the eastern coastal areas to the central and western regions. In 2018, they were concentrated in Inner Mongolia, Liaoning, Henan, Hebei, and other provinces, traditionally large industrial and resource reserve provinces with severe environmental conditions. The pollution level is transferred to the surrounding areas. The provinces with a "low-low" concentration pattern of ecological pollution are mainly Gansu, Guizhou, Xinjiang, and

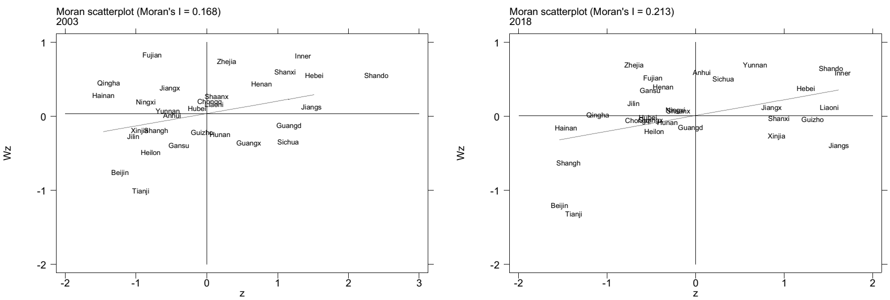

Fig. 2 Local Spatial Correlation Test of Environmental Pollution In 2003 (a) and 2018 (b)

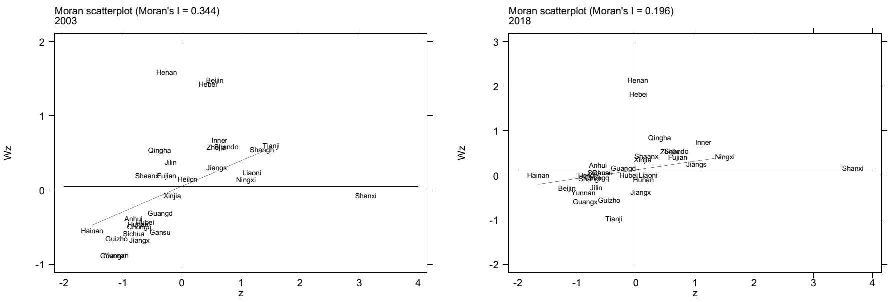

Fig. 3 Local Spatial Correlation Test of Environmental Pollution-intensive Industrial Agglomeration In 2003 (a) and 2018 (b)

other central and western regions, Beijing, Tianjin, and other municipalities with strong environmental regulations.

As shown in Fig. 3, the local spatial correlation test results of pollution-intensive industrial agglomeration in 2003 and 2018 show that all provinces are located in the first and third quadrants, indicating that China's pollution-intensive industrial agglomeration has a robust spatial autocorrelation. In 2018, the provinces with "high-high" agglomeration patterns mainly had environmental pollution agglomeration, such as Inner Mongolia, Hebei, Henan, and Liaoning. Combined with the results of 2003, it can be seen that the concentration of pollution-intensive industries is gradually moving from the southeast to the central and western parts of the country. Provinces with "low-low" agglomeration patterns are mainly provinces with weak industrial bases, such as Guangxi, Yunnan, Guizhou, and other provinces, which are not conducive to forming industrial clusters.

Spatial and Temporal Pattern Evolution Characteristics of Environmental Pollution and Pollution-Intensive Industrial Agglomeration

Arcgis natural breakpoints were used to classify the pollution emission intensity and pollution-intensive industrial agglomeration level of 30 provinces in China into five groups: high-intensity, medium-intensity, medium-intensity, medium–low intensity, and low-intensity areas. It is found that from 2003 to 2018, Shanxi, Inner Mongolia, Hebei, Shandong, and Liaoning provinces have been high-intensity areas and medium intensity areas of pollution emissions, probably due to being resource-based cities whose development needs to rely on the development of resources, so pollution emissions have been high. In addition, we can see that the regional pollution intensity level in the central and northwestern provinces immediately adjacent to the eastern coastal region has increased from low to medium intensity to medium to high intensity, for example, Xinjiang Chongqing, Jiangxi, Anhui, and other provinces. It can be seen that the evolution of the temporal pollution pattern is consistent with the direction of migration of the center of gravity of the average concentration rate of pollution that we found before.

We do a hierarchical treatment of pollution-intensive industrial agglomeration and find that the pollution-intensive industrial agglomeration high-intensity areas are provinces such as Inner Mongolia, Shandong, Liaoning, and Jiangsu, with consistent findings with the distribution of pollution levels. The reason may be that Inner Mongolia, Shanxi, Hebei, and Liaoning provinces mostly rely on the development and processing of resources, so the level of pollution-intensive industrial agglomeration has been high for a long time.; low-intensity areas are Qinghai, Gansu, etc. From 2003 to 2018, the central provinces have risen by one notch. The overall trend of pollution-intensive industrial agglomeration has a development pattern transfer to the west and central parts of the country. The evolution of provincial agglomeration levels is a dynamic process, so it is highly relevant to implement differentiated and customized emission reduction policies in line with the evolution pattern according to the different actual conditions of the provinces (Fig. 4).

Standard Deviation Ellipse

In this paper, we adopt the standard deviation ellipse to explore the pollution and pollution-based industrial agglomeration center of gravity shift status, where x_i

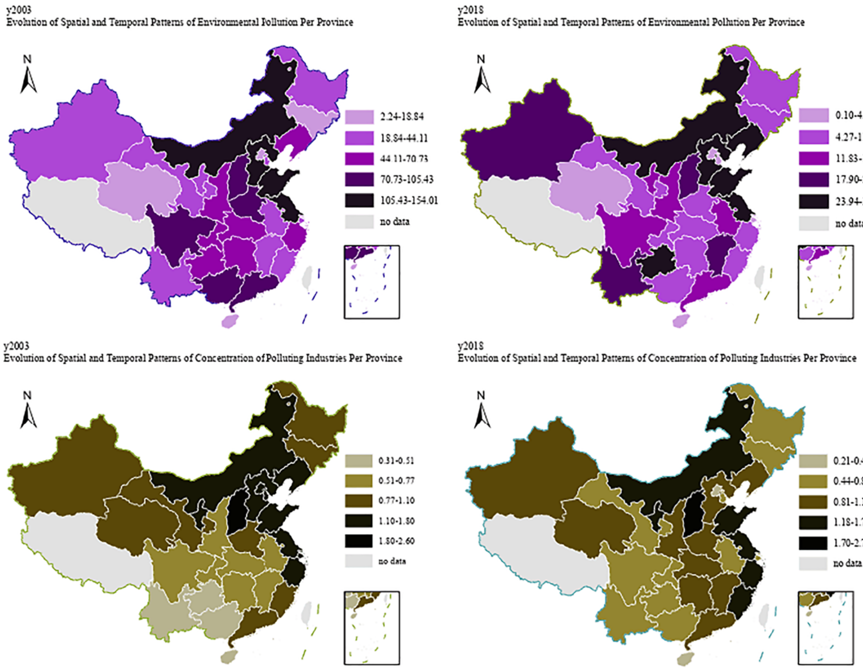

Fig. 4 Evolution of Spatial and Temporal Patterns of Environmental Pollution and Pollution-intensive Industrial Agglomeration

and y_i are the coordinates of the study area i, $\overline{x_i}$ and $\overline{y_i}$ are the deviations of coordinates from the object to the weighted average center, n is the number of provinces, and σ_x σ_y are the standard deviations of the x-axis and y-axis, respectively.

$$\sigma_x = \sqrt{\frac{\sum_{i=1}^{n} (w_i\overline{x_i}\cos\theta - w_i\overline{y_i}\sin\theta)^2}{\sum_{i=1}^{n} w_i^2}} \tag{12}$$

$$\sigma_y = \sqrt{\frac{\sum_{i=1}^{n} (w_i\overline{x_i}\sin\theta - w_i\overline{y_i}\cos\theta)^2}{\sum_{i=1}^{n} w_i^2}} \tag{13}$$

As can be seen in Fig. 5, the overall center of gravity of environmental pollution in China moved from (113.64°E, 35.29°N) in 2003 to (112.28°E, 34.37°N) in 2018, and the spatial rotation angle increased from 21.81° to 98.73°, gradually approaching from the center of Henan to the border of Henan-Shanxi. It indicates that the center of gravity of environmental pollution has progressively moved from the southeastern coastal department to the central and western parts in the past 15 years. The area expanded from 328.79 million km^2 in 2003 to 330.96 million km^2 in 2013 to 328.57 million km^2 in 2018, and the pollution shows a trend of constant expansion and then gradual reduction. This shows that the Chinese government's initiatives for environmental management and green economic development have achieved remarkable results in recent years.

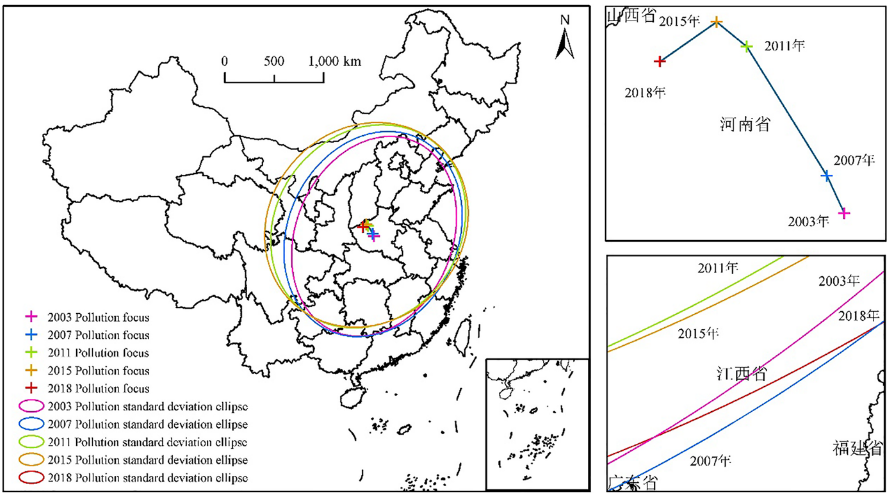

Fig. 5 Migration of the Center of Gravity of the Average Concentration of Pollution

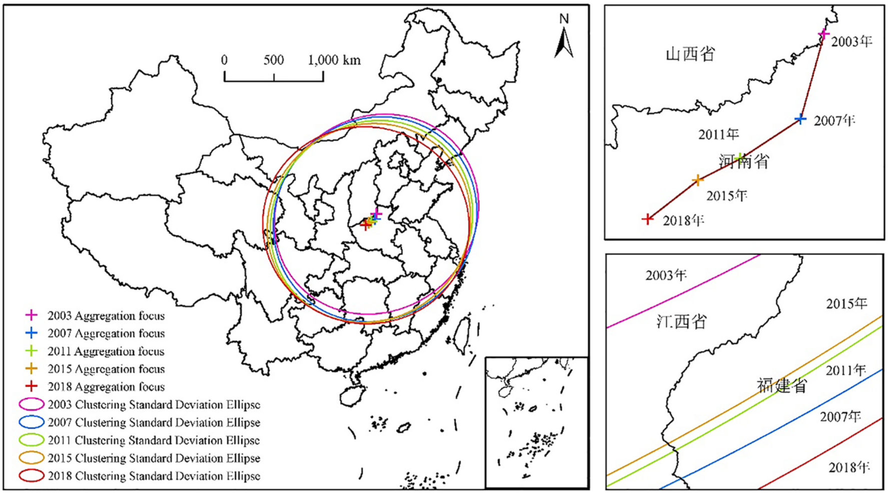

Fig. 6 Relocation of Pollution-intensive Industrial Focus

As shown in Fig. 6, the distribution of pollution-intensive industrial agglomeration in 2003 is significantly smaller than in 2018. The long half-axis increases from 1043.97 km in 2003 to 1143.68 km in 2018, and the sharp half-axis increases from 792.52 km in 2003 to 1035.5 km in 2018, indicating the trend of industrial distribution in 2018 compared to the 2003 year is more prominent. Meanwhile, the area increased from 259.91 million km^2 in 2003 to 372.03 million km^2 in 2018. Pollution-intensive industrial clustering circles are growing, which is consistent with the cluster development strategy advocated by the Chinese government in recent years. In terms of the overall layout center of gravity, the center of gravity of pollution-intensive industries has linearly migrated from the border of Henan and Hebei to the edge of Henan and Shanxi from (113.17°E, 33.55°N) in 2003 to (112°E, 34.31°N) in 2018. The spatial rotation angle increases from 22.81° to 52.33°, gradually showing a migration trend from the east coast to the central and west, almost the same direction as the center of gravity of environmental pollution.

Spatial Econometric Regression Analysis

The Hausman test formula (1) was applied, and the original hypothesis was rejected. That is, the random effect was denied, so the fixed effect regression was adopted. The LR and Wald tests failed the original hypothesis, so the spatial Durbin model was selected. The spatial Durbin model with space–time fixed is judged to fit best according to R^2, so the Durbin model with space–time fixed is selected. Combining the estimated results of the regression coefficients of the explanatory variables and the decomposed direct and indirect effects, the specific effects of environmental regulation and pollution-intensive industrial agglomeration on environmental pollution are analyzed, and the decomposition results of the impact of each variable on the level of environmental pollution are shown in Table 5.

Table 5 Spatial Panel Durbin Model Econometric Regression Results

	Space fixed	Time fixed	Time and Space fixed
L.Pollution		1.51^{***}	1.20^{***}
		(0.02)	(0.04)
ER	-0.09^{**}	-0.42^{***}	-0.14^{***}
	(0.04)	(0.01)	(0.02)
IA	0.56^{**}	0.79^{***}	1.10^{***}
	(0.28)	(0.09)	(0.16)
IA^2	-0.16^{*}	-0.45^{***}	-0.38^{***}
	(0.10)	(0.03)	(0.05)
P	-0.59^{*}	0.10^{***}	0.90^{***}
	(0.34)	(0.03)	(0.20)
Wage	0.81^{***}	-0.39^{***}	0.62^{***}
	(0.19)	(0.05)	(0.12)
T	-0.13^{***}	-0.46^{***}	-0.14^{***}
	(0.02)	(0.01)	(0.01)
Open	2.95^{**}	54.03^{***}	15.90^{***}
	(1.38)	(0.65)	(0.77)
W*ER	-0.10	-1.40^{***}	-0.56^{***}
	(0.08)	(0.03)	(0.05)
W*IA	-2.43^{***}	-1.74^{***}	2.41^{***}
	(0.55)	(0.17)	(0.32)
$W*IA^2$	0.50^{***}	0.55^{***}	-0.61^{***}
	(0.17)	(0.06)	(0.10)
W*P	-0.81	3.31^{***}	3.73^{***}
	(0.67)	(0.06)	(0.39)
W*Wage	-0.59^{***}	-1.31^{***}	2.73^{***}
	(0.22)	(0.10)	(0.28)
W*T	0.08^{***}	-1.15^{***}	-0.50^{***}
	(0.03)	(0.01)	(0.02)
W*Open	-2.60	138.36^{***}	65.54^{***}
	(2.71)	(1.29)	(1.53)
ρ	0.67^{***}	0.17^{***}	0.46^{***}
	(0.03)	(0.04)	(0.05)
N	480	450	450
R^2	0.147	0.261	0.483

Standard errors in parentheses

* $p<0.1$, ** $p<0.05$, *** $p<0.01$

First, the spatial coefficients of the explanatory variables are significantly positive, indicating that environmental pollution has a significant spatial spillover effect in each province of China. It means that when the ecological pollution condition in one province deteriorates further, the environmental pollution level in the neighboring provinces and regions will increase further. The environmental pollution condition has a spatial linkage effect. Second, the regression coefficient of the ecological regulation intensity of each province is significantly harmful. It indicates that when the level of environmental regulation is further strengthened, it can have an overall suppressive effect on the environmental pollution level in the province. The spatial spillover effect is significantly negative, indicating that the intensity of environmental regulations in the province ameliorates the pollution status of neighboring provinces. This spillover effect is spatially bi-directional, and the province usually borrows and imitates the practical measures of environmental management from neighboring provinces, which will lead to a more balanced role of environmental regulation in the global or region-wide context and further improve the restraining effect on the deteriorating environmental pollution problem globally, which is consistent with (Blackman & Bannister, 1998; Peng et al., 2018) findings, and hypothesis H1 is verified.

Finally, the regression coefficient of the agglomeration level of pollution-intensive industries is significantly positive. The coefficient of its squared term is highly negative, indicating a significant inverted "U" curve relationship between the agglomeration of pollution-intensive sectors and the level of environmental pollution. As the agglomeration level of high pollution industries increases, the emission of pollutants also increases rapidly, which leads to the rise of environmental pollution levels. However, along with the rise in the level of agglomeration, industrial agglomeration improves production efficiency through specific scale effects and reduces input materials and costs while expanding the scale of production, thus reducing pollution or providing financial support for environmental pollution prevention and control; the increase in the level of industrial agglomeration improves environmental protection innovation technology, reduces energy consumption, and improves the total utilization rate and centralized treatment rate of pollutants, which further plays a role in ecological improve the position. The direct and spatial spillover effects of industrial agglomeration are significantly positive, implying that when the level of local pollution-intensive industrial agglomeration increases, the deterioration of local environmental pollution will further intensify, while there will be some spillover effects on neighboring provinces, and hypothesis H2 is verified.

The effects of control variables on environmental pollution: ① Total population (P) is significantly positive in both direct and spatial spillover effects. It means that the increase of the total population in this province will make the pollution emission in this province increase, and at the same time will have some spillover effect on the surrounding provinces. The growth of the population base brings an increase in resource consumables, thus making the province’s pollution-intensive industries further expand their markets, which leads to further worsening of the pollution deterioration (Liu & Pei, 2017). Meanwhile, the growth of the total population in the province leads to population migration to neighboring provinces, which increases the consumption of resource consumables and leads to pollution spillover; (ii) the per capita income level (Wage) is significantly positive in both the direct effect and spatial spillover effect. The increase in the per capita income of residents in this province leads to the rise in purchasing power and the expansion of market potential, leading to a rise in household and industrial consumer goods.

On the one hand, consumers' increased consumption of domestic and industrial goods leads to a portion of pollution emissions as manufacturers further expand production to meet market demand. The intensity of pollution emissions from industrial production increases.

On the other hand, purchasing power will increase demand for industrial and household goods from surrounding provinces to satisfy the local market. Considering the transportation distance and other factors, it will make the polluting industries in neighboring provinces further expand their production, thus leading to pollution spillover effects; ③ The direct and spatial impacts of science and technology input (T) are unfavorable. The increase of science and technology input (T) implies the proliferation of technological innovation in the province. Technological innovation has positive externalities and innovation compensation effects on pollution emissions (Testa et al., 2011). The coefficients of direct and spatial impacts of foreign direct investment (Open) are significantly positive, indicating that the introduction of foreign direct investment directly aggravates the environmental pollution in the province and has a specific spillover effect on the surrounding provinces. Based on the "pollution paradise" hypothesis, pollution-intensive industries tend to be established in areas with lower environmental standards (Walter & Ugelow, 1979). In the case of a large amount of foreign investment in the province, the environmental friendliness of the imported foreign investment and the environmental control of the industry are often neglected (List & Co, 2000). Moreover, according to the National Bureau of Statistics, it is concluded that the share of manufacturing industries in the practical foreign investment introduced in China is 30%. It is evident that FDI introduced in China is mainly concentrated in pollution-intensive sectors such as manufacturing, which plays a further worsening role in environmental pollution (Dellachiesa & Myint, 2016; López et al., 2018; Sarkodie & Strezov, 2019).

Heterogeneity Regression Analysis under the Difference of Economic Development Level

Do the effects of environmental regulations on environmental pollution show significant differences depending on each Chinese province's economic development level? Here, we refer to (Du et al., 2021) to consider the heterogeneity effect caused by each province's different levels of economic development. The average GDP per capita of each province in 2018 is used as the boundary. The sample is roughly divided into "economically developed provinces" and "economically less developed provinces" to consider the important effect of the level of economic development. The regression results are shown in the table below. The results show that the impact of environmental regulations on environmental pollution is still consistent with the above findings in both economically developed and less developed provinces, and the effect of environmental regulations on environmental pollution reduction is more obvious in economically developed provinces. The main reason for this phenomenon is that economically developed provinces have more obvious technological and financial advantages, have more quality resources for production technology improvement and green technology innovation when subjected to environmental regulations, and are more capable of industrial structure optimization and adjustment.

Effect Decomposition Measures

When the spatial lag coefficient is not zero, the regression coefficients of the explanatory variables do not accurately reflect the effects on the explanatory variables Lesage and Pace (2009). In order to accurately estimate the impact of environmental regulation and the concentration of polluting industries on environmental pollution, this study conducted an effect decomposition based on the SDM model, which decomposed the effects of environmental regulation and polluting industrial agglomeration on environmental pollution into direct and indirect effects in the long and short term, respectively. The immediate result represents the impact of environmental regulation intensity and polluting industrial agglomeration on environmental pollution in the province; the indirect effect represents environmental regulation intensity and polluting industrial agglomeration on environmental pollution in the neighboring provinces.

The effect decomposition measures are shown in Table 6 below. The dynamic Durbin model can be used for both direct and indirect effect estimation in the long and short term (Elhorst, 2014). The long- and short-term effects show both the state of long-term equilibrium and the analysis of short-term changes, which is an important analytical tool to identify the differences between long- and short-term. As can be seen from the table, the long-term effects fail the test more than the number of short-term failures, so in the whole system of effects, long-term equilibrium is only a theoretical expectation, which is not reached in practice and is still dominated by short-term effects.

In the short term, both the direct and indirect effects of environmental regulation are significant and negative, indicating that the higher the intensity of environmental regulation in the province, the environmental pollution in the province can be significantly improved, but not only within the province, with the expansion of geographic distance, the spatial spillover effect is also significant; both the direct and indirect impacts of polluting industrial agglomeration are substantial and positive, indicating that the higher the level of polluting industrial agglomeration in the province The higher the level of environmental pollution in the province, the higher the level of environmental pollution in the province, and the spatial spillover effect on neighboring provinces. At the same time, the squared terms of the agglomeration level of polluting industries are significantly negative, indicating that the agglomeration of polluting industries and environmental pollution show an inverted "U" curve relationship, i.e., as the agglomeration level increases, the level of environmental pollution will increase. However, as the agglomeration level continues to rise, environmental pollution will gradually decrease. The direction of action is consistent with the dynamic SDM model coefficients in the short run. In the long run, environmental regulation and polluting industrial agglomeration are insignificant to environmental

Table 6 Heterogeneity regression analysis under the difference of economic development level

Variable	Less economically developed provinces	Economically developed provinces
L.Pollution	1.60***	1.20***
	(0.02)	(0.04)
ER	-0.02**	-0.14***
	(0.01)	(0.02)
IA	0.52***	1.10***
	(0.02)	(0.16)
IA^2	-0.12***	-0.38***
	(0.08)	(0.05)
P	-0.65***	0.90***
	(0.17)	(0.20)
Wage	0.62***	0.62***
	(0.12)	(0.12)
T	-0.08***	-0.14***
	(0.01)	(0.01)
Open	3.95***	15.90***
	(0.60)	(0.77)
W*ER	-0.07***	-0.56***
	(0.02)	(0.05)
W*IA	1.56***	2.41***
	(0.25)	(0.32)
$W*IA^2$	-0.55***	-0.61***
	(0.08)	(0.10)
W*P	2.55***	3.73***
	(0.19)	(0.39)
W*Wage	1.65***	2.73***
	(0.15)	(0.28)
W*T	0.01	-0.50***
	(0.00)	(0.02)
W*Open	10.55***	65.54***
	(2.32)	(1.53)
ρ	0.58***	0.46***
	(0.08)	(0.05)
N	450	450
R^2	0.292	0.483

Standard errors in parentheses

* $p<0.1$, ** $p<0.05$, *** $p<0.01$

pollution. Still, the total effect is significant, and the impact of environmental regulation and polluting industrial agglomeration on environmental pollution is persistent. The total impact of environmental regulation is negative. In the long term, as the intensity of environmental regulation in each province increases, the awareness of

Table 7 Effect Decomposition Measures

Variable	Decomposition of Short-term Effects			Decomposition of Long-term Effects		
	Direct effect	Indirect effect	Total effect	Direct effect	Indirect effect	Total effect
ER	-0.09***	-0.39***	-0.48**	0.16	-2.95	-2.78**
IA	0.89***	1.55***	2.44***	-2.68	16.94	14.26***
IA^2	-0.34***	-0.36***	-0.69***	26.79	-5.19	-4.06***

* $p<0.1$, ** $p<0.05$, *** $p<0.01$

polluting industries on pollution emission is deepening. Thus, ecological pollution emission is decreasing; the total effect of polluting industrial agglomeration level is significantly positive, and its squared term coefficient is significant and negative, which can still be verified in the long term to prove the inverted "U" curve relationship between pollution-intensive industrial agglomeration and environmental pollution. "U" curve relationship (Table 7).

Endogenous Discussion

Since provinces with high environmental pollution tend to be economically developed regions, the intensity of environmental regulations in developed regions may be increased by the deterioration of environmental pollution. In addition, developed provinces may be attractive to pollution-intensive industries and produce agglomeration effects, i.e., reverse causality may occur, leading to biased and unreliable regression estimation results. Therefore, this paper adopts the instrumental variables approach to address the endogeneity problem.

It has been shown that the government, through tax exemptions, preferential tax rates, and low tax policies, attracts enterprises from inside and outside the region and plays a role in promoting industrial clustering to achieve the purpose of regional economic development (Wang & Yan, 2014). Similarly, each province's fixed asset investment or capital stock can drive industrial agglomeration. At the same time, provincial tax revenue and fixed asset investment can effectively increase the intensity of environmental regulation because, on the one hand, provinces with higher tax revenues or fixed asset investments have more resources for environmental management. On the other hand, the more environmental protection taxes are levied on some heavy polluters, the greater the intensity of environmental regulation. However, the tax revenue and fixed asset investment of Chinese provinces do not directly contribute to environmental pollution, and there are no direct relationships between tax revenue, fixed asset investment and environmental pollution. Therefore, in this paper, tax revenue (TR) and fixed asset investment (FAI) are selected as instrumental variables to solve the possible endogeneity among environmental regulation, polluting industrial agglomeration, and environmental pollution.

Meanwhile, we adopt a 2SLS estimation to address the endogeneity problem, and the regression results are shown in Table 8. The regression results of the instrumental variables are reported in the table below. The significant value of LM in the

Table 8 Instrumental variable test results

Variable	First stage of regression		Second stage of regression
	ER	IA	Pollution
ER			-0.83*** (0.02)
IA			1.89*** (0.65)
TR	0.206*** (0.06)	-0.64*** (0.15)	
FAI	0.373*** (0.02)	0.106** (0.01)	
Control variables	✓	✓	✓
Year	✓	✓	✓
Individual	✓	✓	✓
Sargan	0.427	0.143	
Wald F statistic			196.12
Kleibergen-Paaprk LM statistic			0.006

Standard errors in parentheses

* $p<0.1$, ** $p<0.05$, *** $p<0.01$

unidentifiable test is 0.006, which is much smaller than the critical value of 0.1, so the original hypothesis of unidentifiability is firmly rejected. The Wald F statistic in the weak instrumental variable test is 196.12, which is greater than the critical value of 10, so the weak instrumental variable problem is rejected. The regression results show that provincial tax revenues are significantly negatively correlated with the agglomeration of polluting industries, which indicates the agglomeration formation of polluting industries promoted by low taxes; taxes are positively correlated with environmental regulations, which indicates that the higher the taxes and fees being levied in the province, the higher the intensity of environmental regulations. Total provincial fixed asset investment is positively correlated with both environmental regulation and industrial agglomeration, consistent with the above discussion. The estimated effects of environmental regulation and polluting industrial agglomeration on environmental pollution remain robust after adding instrumental variables and controlling for time and individuals.

Robustness Regression

Numerous scholars tend to use transformed spatial matrices for robustness testing in spatial measures. Therefore, in this section, the spatial matrix is converted into an economic spatial matrix before performing the SDM model test. The test results and effective measures are shown in Tables 9 and 10. the same conclusive results as before can be drawn from the regression results in the tables, which have not changed, indicating that this paper's results are robust.

Table 9 Economic Space Matrix Spatial Panel Durbin Model Regression Results

	Space fixed	Time fixed	Time and Space fixed
L.Pollution		1.49***	1.32***
		(0.02)	(0.04)
ER	-0.06*	-0.61***	-0.15***
	(0.04)	(0.01)	(0.02)
IA	0.69***	1.37***	0.90***
	(0.26)	(0.09)	(0.16)
IA^2	-0.18*	-0.51***	-0.34***
	(0.09)	(0.03)	(0.05)
P	-0.48	0.08***	0.21
	(0.33)	(0.03)	(0.21)
Wage	0.88***	-1.37***	0.30**
	(0.18)	(0.05)	(0.12)
T	-0.12***	-0.52***	-0.12***
	(0.02)	(0.01)	(0.01)
Open	2.44*	56.35***	10.99***
	(1.32)	(0.64)	(0.80)
W*ER	-0.07	-2.73***	-0.54***
	(0.07)	(0.03)	(0.05)
W*IA	-2.10***	-2.78***	2.32***
	(0.62)	(0.21)	(0.39)
$W*IA^2$	0.38*	1.07***	-0.61***
	(0.22)	(0.07)	(0.13)
W*P	-1.44*	5.04***	3.87***
	(0.76)	(0.07)	(0.51)
W*Wage	-0.66***	-5.41***	2.79***
	(0.20)	(0.12)	(0.33)
W*T	0.07**	-2.15***	-0.59***
	(0.03)	(0.02)	(0.02)
W*Open	0.49	260.74***	68.83***
	(3.22)	(1.84)	(2.02)
ρ	0.73***	0.42***	0.98***
	(0.03)	(0.05)	(0.06)
N	480	450	450
R^2	0.088	0.201	0.474

Standard errors in parentheses

$^{*}p<0.1$, $^{**}p<0.05$, $^{***}p<0.01$

Conclusions

Based on environmental regulation theory, industrial agglomeration theory, and spatial economic theory, this paper explores the transfer of industrial

Table 10 Effect Decomposition Measures under the Economic Matrix

Variable	Decomposition of Short-term Effects			Decomposition of Long-term Effects		
	Direct effect	Indirect effect	Total effect	Direct effect	Indirect effect	Total effect
ER	-0.06***	-0.29***	-0.35**	-0.49	-0.57	-1.05**
IA	0.54***	1.11***	1.65***	1.54	3.47	5.00***
IA^2	-0.27***	-0.21***	-0.49***	-0.36	-1.12	-1.48***

* $p<0.1$, ** $p<0.05$, *** $p<0.01$

agglomeration and the center of gravity of environmental pollution from the perspective of spatial spillover, and adopts a dynamic spatial measurement method to find that environmental regulation has a significant inhibitory effect on environmental pollution and there is a negative spatial spillover effect; and further focuses on pollution-intensive industries to identify the existence of a The paper further focuses on pollution-intensive industries and identifies a nonlinear mechanism between the concentration of polluting industries and environmental pollution. This paper explores the comprehensive relationship between environmental regulation, industrial agglomeration, and environmental pollution from the perspective of spatial spillover, and tries to depict the mechanism of environmental regulation and industrial agglomeration on environmental pollution in a more three-dimensional and dynamic way, which enriches the theory of environmental regulation and industrial agglomeration to a certain extent. The main research findings are as follows.

First, environmental pollution and pollution-intensive industries in all Chinese provinces have significant spatial autocorrelation and significant spatial linkage effects. Among them, provinces with "high-high" agglomeration patterns of environmental pollution include Inner Mongolia, Liaoning, Henan, Hebei, and other large resource-reserve industrial provinces; provinces with "low-low" agglomeration patterns are mainly concentrated in Gansu, Guizhou, Xinjiang, and other provinces with a weak industrial base. The standard deviation ellipse model shows that the center of gravity of environmental pollution and pollution-intensive industries tend to migrate from the southeastern coastal provinces to the central and western provinces with rich resource reserves.

Second, this paper uses the entropy power method to comprehensively measure the intensity of environmental regulation, and through dynamic spatial econometric empirical analysis, it is concluded that environmental regulation has a significant inhibitory effect on environmental pollution in the province, and there is a negative spatial spillover effect, i.e., environmental regulation in the province will also further alleviate the environmental pollution in neighboring provinces. In addition, it is verified that there is a significant inverse "U" nonlinear relationship between the agglomeration level of pollution-intensive industries and environmental pollution in China, which means that the increase in the agglomeration level will lead to a sharp increase in environmental pollution, but as the agglomeration level increases to a certain level, the positive externalities of the agglomeration to environmental pollution will be greater than its negative externalities, i.e. environmental pollution is improved through technology and knowledge spillover effects.

Finally, the increase in population density, per capita income, and foreign direct investment all intensify environmental pollution and have some spatial spillover effects on neighboring provinces, while the increase in science and technology investment significantly suppresses environmental pollution and has an overall improvement on environmental pollution.

Policy Implications

Based on the above analysis, to improve the environmental pollution situation, this study makes recommendations in the following aspects.

(1) While environmental pollution and pollution-intensive industries are transferred to central and western China, it is recommended that provinces should increase the intensity of environmental regulation and establish a perfect environmental pollution governance mechanism in advance (Shen & Zhou, 2020). The state should encourage the central and western provinces to learn the experience of environmental governance and implement it into the environmental pollution governance of the province while transferring environmental technology from coastal areas to avoid the situation of pollution first and governance later.

(2) The environmental pollution situation in this province is not only influenced by the intensity of environmental regulations in this region but also the intensity of environmental regulations in neighboring provinces has a certain improvement effect on the environmental pollution in this province. Therefore, when formulating environmental regulation policies for this province, we should focus on the synergistic governance and emission reduction of multiple provinces, establish a joint regulatory prevention system of cross-regional communication, learning and exchange, deepen the full cooperation of each region, and jointly build and improve an efficient, shared and win–win environmental pollution governance planning system.

(3) The energy-saving and emission reduction effects of industrial agglomeration on environmental pollution should be viewed objectively. For provinces with different pollution-based industrial agglomeration levels, differentiated and tiered governance measures should be implemented. The eastern coastal provinces with lower agglomeration levels should further agglomerate domestic science and technology innovation companies, accelerate the pace of green technology innovation, strive to build green, intelligent, and shared industrial development clusters, and further realize the upgrading of polluting industrial structures(Ehrenfeld, 2003); while provinces with higher agglomeration levels, such as Ningxia and Inner Mongolia, can continue to attract investment and further expand the scale of the agglomeration economic circle. While further expanding the scale of agglomeration, the pollution spillover from the agglomeration of pollution-intensive industries cannot be ignored. In view of

the emission effects of diversified agglomeration on environmental pollution, it is recommended that a sound mechanism for centralized management of pollutants be established in advance to focus on improving environmental protection technologies and reducing environmental pollution emissions.

(4) The state should improve environmental standards for the introduction of foreign investment, reduce the introduction of highly polluting and efficient foreign enterprises, and continuously increase the proportion of introduction of environmentally friendly or high-end technology industries as well as environmental access standards (List & Co, 2000). Further, increasing the structural share of renewable and new energy sources, and emission reduction targets can be achieved gradually by transforming the energy system to clean energy. At the same time, increase the investment in science and technology innovation in each province to improve the environmental situation through the positive externalities brought by the compensating effect of technological innovation.

Funding This research is funded by the general program of National Natural Science Foundation of China (71974083) and Hangzhou Normal University Scientific Research Start-up Project.

Declarations

Conflicts of interest The authors do not have any possible conflicts of interest.

References

Ambec, S., Cohen, M. A., Elgie, S., & Lanoie, P. (2013). The Porter hypothesis at 20: Can environmental regulation enhance innovation and competitiveness? *Review of Environmental Economics and Policy, 7*(1), 2–22.

Blackman, A., & Bannister, G. J. (1998). Community pressure and clean technology in the informal sector: An econometric analysis of the adoption of propane by traditional Mexican brickmakers. *Journal of Environmental Economics and Management, 35*(1), 1–21.

Chen, H., Hao, Y., Li, J., & Song, X. (2018). The impact of environmental regulation, shadow economy, and corruption on environmental quality: Theory and empirical evidence from China. *Journal of Cleaner Production, 195*, 200–214.

Copeland, B. R., & Taylor, M. S. (2004). Trade, growth, and the environment. *Journal of Economic Literature, 42*(1), 7–71.

Dai, Q., Qang, J., Zhang, X., & Hu, S. (2020). Transfer characteristics, patterns and mechanisms of polluting enterprises and industries. *Geography and Natural Resources, 39*(7), 1511–1533.

Dasgupta, S., Laplante, B., Mamingi, N., & Wang, H. (2001). Inspections, pollution prices, and environmental performance: Evidence from China. *Ecological Economics, 36*(3), 487–498.

Dellachiesa, A. E., & Myint, A. P. (2016). Trade openness and the changing water polluting intensity patterns of 'dirty'and 'clean'industrial sectors. *Ecological Economics, 129*, 143–151.

Du, K., Cheng, Y., & Yao, X. (2021). Environmental regulation, green technology innovation, and industrial structure upgrading: The road to the green transformation of Chinese cities. *Energy Economics, 98*, 105247.

Ehrenfeld, J. (2003). Putting a spotlight on metaphors and analogies in industrial ecology. *Journal of Industrial Ecology, 7*, 1–4.

Elahi, E., Weijun, C., Jha, S. K., & Zhang, H. (2019). Estimation of realistic renewable and non-renewable energy use targets for livestock production systems utilising an artificial neural network method: A step towards livestock sustainability. *Energy, 183*, 191–204.
Elgin, C., & Mazhar, U. (2013). Environmental regulation, pollution and the informal economy. *Social Behavior and Personality Research Bulletin, 9*, 62–81.
Elhorst, J. P. (2014). *Spatial econometrics: from cross-sectional data to spatial panels* (Vol. 479), p. 480). Springer.
Feng, T., Du, H., Lin, Z., & Zuo, J. (2020). Spatial spillover effects of environmental regulations on air pollution: Evidence from urban agglomerations in China. *Journal of Environmental Management, 272*, 110998.
Han, J., Sun, Y. W., Chen, C. F., & Lan, Q. X. (2019). Does Industrial Upgrading Promote the Green Growth of Chinese Cities. *Journal of Beijing Normal University(Social Sciences)*, 139–151.
Jalil, A., & Feridun, M. (2011). The impact of growth, energy and financial development on the environment in China: A cointegration analysis. *Energy Economics, 33*(2), 284–291.
Johnson, K. M., Voss, P. R., Hammer, R. B., Fuguitt, G. V., & McNiven, S. (2005). Temporal and spatial variation in age-specific net migration in the United States. *Demography, 42*(4), 791–812.
Karkalakos, S. (2010). Capital heterogeneity, industrial clusters and environmental consciousness. *Journal of Economic Integration*, 353–375.
Krugman, P. (1998). Space: The Final Frontier. *Journal of Economic Perspectives, 12*(2), 161–174.
Leiter, A. M., Parolini, A., & Winner, H. (2011). Environmental regulation and investment: Evidence from European industry data. *Ecological Economics, 70*(4), 759–770.
LeSage, J., & Pace, R. K. (2009). *Introduction to spatial econometrics*. Chapman and Hall/CRC.
List, J. A., & Co, C. Y. (2000). The effects of environmental regulations on foreign direct investment. *Journal of Environmental Economics and Management, 40*(1), 1–20.
List, J. A., Millimet, D. L., Fredriksson, P. G., & McHone, W. W. (2003). Effects of environmental regulations on manufacturing plant births: Evidence from a propensity score matching estimator. *Review of Economics and Statistics, 85*(4), 944–952.
Liu, H., & Pei, Y. (2017). Environmental Kuznets curve test of haze pollution in China. *Statistical Research, 3*, 47–56.
López, L. A., Arce, G., Kronenberg, T., & Rodrigues, J. F. (2018). Trade from resource-rich countries avoids the existence of a global pollution haven hypothesis. *Journal of Cleaner Production, 175*, 599–611.
Marshall, A. (1920). *Principles of Economics* (p. 8). Macmillan and Co., Ltd.
Milani, S. (2017). The impact of environmental policy stringency on industrial R&D conditional on pollution intensity and relocation costs. *Environmental and Resource Economics, 68*(3), 595–620.
Palmer, K., Oates, W. E., & Portney, P. R. (1995). Tightening environmental standards: The benefit-cost or the no-cost paradigm? *Journal of Economic Perspectives, 9*(4), 119–132.
Pei, Y., Zhu, Y., Liu, S., & Xie, M. (2021). Industrial agglomeration and environmental pollution: Based on the specialized and diversified agglomeration in the Yangtze River Delta. *Environment, Development and Sustainability, 23*(3), 4061–4085.
Peng, B., Tu, Y., Elahi, E., & Wei, G. (2018). Extended Producer Responsibility and corporate performance: Effects of environmental regulation and environmental strategy. *Journal of Environmental Management, 218*, 181–189.
Porter, M. (1996). America's green strategy. *Business And The Environment: A Reader, 33*, 1072.
Porter, M. E., & Van der Linde, C. (1995). Toward a new conception of the environment-competitiveness relationship. *Journal of Economic Perspectives, 9*(4), 97–118.
Ramanathan, R., He, Q., Black, A., Ghobadian, A., & Gallear, D. (2017). Environmental regulations, innovation and firm performance: A revisit of the Porter hypothesis. *Journal of Cleaner Production, 155*, 79–92.
Saltari, E., & Travaglini, G. (2011). The effects of environmental policies on the abatement investment decisions of a green firm. *Resource and Energy Economics, 33*(3), 666–685.
Sarkodie, S. A., & Strezov, V. (2019). Effect of foreign direct investments, economic development and energy consumption on greenhouse gas emissions in developing countries. *Science of the Total Environment, 646*, 862–871.
Shen, K. R., & Zhou, L. (2020). Local government competition, vertical environmental regulation and the pollution backflow effect. *Economic Research Journal, 3*, 35–49.
Shen, N., & Peng, H. (2021). Can industrial agglomeration achieve the emission-reduction effect? *Socio-Economic Planning Sciences, 75*, 100867.

Sinn, H. W. (2008). Public policies against global warming: A supply side approach. *International Tax and Public Finance, 15*(4), 360–394.

Tarokh, V., Seshadri, N., & Calderbank, A. R. (1998). Space-time codes for high data rate wireless communication: Performance criterion and code construction. *IEEE Transactions on Information Theory, 44*(2), 744–765.

Testa, F., Iraldo, F., & Frey, M. (2011). The effect of environmental regulation on firms' competitive performance: The case of the building & construction sector in some EU regions. *Journal of Environmental Management, 92*(9), 2136–2144.

Van Doorn, J., & Verhoef, P. C. (2008). Critical incidents and the impact of satisfaction on customer share. *Journal of Marketing, 72*(4), 123–142.

Walter, I., & Ugelow, J. L. (1979). Environmental policies in developing countries. *Ambio*, 102–109.

Wang, B., & Nie, X. (2016). Industrial Agglomeration and Environmental Governance: The Power or Resistance—Evidence from a Quasi-natural Experiment of Establishment of the Development Zone. *China Industrial Economics, 12*, 75–89.

Wang, J., Feng, J., Yan, Z., Hu, Y., & Jia, G. (2012). Nested high-resolution modeling of the impact of urbanization on regional climate in three vast urban agglomerations in China. *Journal of Geophysical Research: Atmospheres*, 117(D21).

Wang, Y. P., & Yan, W. L. (2014). The Tax Avoidance Effect of Industrial Agglomeration—Empirical Evidence from China's Manufacturing Enterprises. *China Industrial Economics, 12*, 87–69. (In Chinese).

Wang, Y., & Wang, J. (2019). Does industrial agglomeration facilitate environmental performance: New evidence from urban China? *Journal of Environmental Management, 248*, 109244.

Whittet, R., Cottrell, J., Cavers, S., Pecurul, M., & Ennos, R. (2016). Supplying trees in an era of environmental uncertainty: Identifying challenges faced by the forest nursery sector in Great Britain. *Land Use Policy, 58*, 415–426.

Willy, D. K., Muyanga, M., & Jayne, T. (2019). Can economic and environmental benefits associated with agricultural intensification be sustained at high population densities? A farm level empirical analysis. *Land Use Policy, 81*, 100–110.

Xiong, Y., Bingham, D., Braun, W. J., & Hu, X. J. (2019). Moran's I statistic-based nonparametric test with spatio-temporal observations. *Journal of Nonparametric Statistics, 31*(1), 244–267.

Zeng, Y., Cao, Y., Qiao, X., Seyler, B. C., & Tang, Y. (2019). Air pollution reduction in China: Recent success but great challenge for the future. *Science of the Total Environment, 663*, 329–337.

Zhang, J., Chang, Y., Zhang, L., & Li, D. (2018). Do technological innovations promote urban green development?—A spatial econometric analysis of 105 cities in China. *Journal of Cleaner Production, 182*, 395–403.

Zhang, S. L., & Zhang, K. (2007). Contrast study on Moran and Getis-Ord indexes of local spatial autocorrelation indices. *Journal of Geodesy and Geodynamics, 27*(3), 31–34.

Zhao, X., & Sun, B. (2016). The influence of Chinese environmental regulation on corporation innovation and competitiveness. *Journal of Cleaner Production, 112*, 1528–1536.

Zheng, Q., & Lin, B. (2018). Impact of industrial agglomeration on energy efficiency in China's paper industry. *Journal of Cleaner Production, 184*, 1072–1080.

Zhou, X., & Feng, C. (2017). The impact of environmental regulation on fossil energy consumption in China: Direct and indirect effects. *Journal of Cleaner Production, 142*, 3174–3183.

Authors and Affiliations

Zheng-Xia He[1] · Chang-Shuai Cao[2] · Jian-Ming Wang[3]

Zheng-Xia He
hezhengxia79@163.com

Jian-Ming Wang
sjwjm@zufe.edu.cn

1 School of Economics, Hangzhou Normal University, Hangzhou, Zhejiang Province 311121, People's Republic of China

2 Business School, Jiangsu Normal University, Xuzhou, Jiangsu Province 221116, People's Republic of China

3 School of Business Administration, Zhejiang University of Finance & Economics, Hangzhou, Zhejiang Province 310018, People's Republic of China