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Abstract: Manufacturing agglomeration promotes rapid economic development while also causing severe environmental pollution. This paper investigates the impact and mechanism of manufacturing agglomeration on haze pollution from the Chinese city level. Furthermore, we discuss the moderating effect and threshold effect of the three urban forms of urban external shape complexity, urban compactness, and urban fragmentation on the relationship between the two. The result shows: (1) The aggregation of the manufacturing industry presents an inverted U-shaped characteristic of promoting first and then inhibiting haze pollution in China's overall, eastern and central regions. (2) The complexity of the city's external shape and the city's fragmentation has a positive moderating effect on the relationship between manufacturing agglomeration and haze pollution. And urban fragmentation shows a negative moderating effect on the relationship between the two when the level of manufacturing agglomeration is on the right side of the inverted U-shaped curve. (3) The urban form shows a significant double threshold characteristic for haze pollution, increasing the complexity of the city's external shape and the city's fragmentation. The agglomeration of manufacturing shows the characteristics of first inhibiting and then promoting haze pollution. As urban compactness increases, the inhibitory effect of manufacturing agglomeration on haze pollution increases.

Keywords: manufacturing agglomeration; urban form; haze pollution; moderating effect; threshold effect

Introduction

Since the Industrial Revolution, the rapid economic and urbanization development in various world regions has also resulted in severe environmental pollution. And air pollution represented by frequent haze weather is particularly prominent (Wang et al. 2015). Haze pollution will seriously affect the daily life and health of residents but also causes incalculable damage to social and economic development (Xu et al. 2022). China is the world's largest developing country, its economic growth relies on traditional manufacturing and fossil energy consumption, and the inefficiency of environmental governance has led to increasingly severe haze pollution (Hao et al. 2022). Therefore, in the face of the threat and trouble of haze pollution, it is necessary to explore the economic root cause of the frequent occurrence of haze pollution and find out the critical factors to control it. And we can take practical measures to improve air quality, thereby safeguarding people's health and promoting sustainable economic development (Zhang et al. 2019).

Manufacturing plays a crucial role in driving regional economies to grow, increase employment opportunities and raise living standards (Haraguchi et al. 2017). At the same time, as an organizational form of modern manufacturing, spatial agglomeration brings various positive externalities such as economies of scale and knowledge spillovers. It helps to optimize the allocation efficiency of production factors of enterprises in agglomeration areas (Chen et al. 2020), thereby reducing the production cost of enterprises and enhancing industrial competitiveness. In terms of China's reality, with the continuous improvement of infrastructure, China's manufacturing agglomeration continues to increase (Hao et al. 2022). And several representative manufacturing clusters have been formed, such as the electronics industry cluster in Guangdong Province and the textile industry cluster in Zhejiang Province (Lan et al. 2021). These representative manufacturing clusters can not only drive the economic growth of the region through economies of scale and agglomeration effects but also radiate and drive the improvement of the economic development level of the surrounding areas. However, industrial agglomeration cannot expand infinitely. When the agglomeration level exceeds the carrying capacity threshold of regional resources and the environment, it may pose a severe threat to the ecological environment (Meng and Xu, 2022). China's haze pollution is mainly concentrated in mega-city clusters such as the Pearl River Delta, Yangtze River Delta and Beijing-Tianjin-Hebei (Song et al. 2017). These regions are also the main agglomeration areas of China's manufacturing industry. So, does this mean that the concentration of manufacturing is the cause of increased haze pollution? Secondly, can industrial agglomeration play a positive role in alleviating haze pollution by various positive externalities such as economies of scale, cost savings, and technology spillovers? At the same time, China has a vast territory, and multiple regions have significant differences in many aspects such as resource endowment, industrial composition, economic development stage, technological level, and market business environment (Dong et al. 2019). Under the influence of the above factors, the agglomeration level of China's manufacturing industry presents the characteristics of unbalanced regional development. So, are there regional variations in the influence of the agglomeration of manufacturing industries on haze pollution in different areas? Therefore, an empirical investigation of the concentration of manufacturing industries on haze pollution in China is conducive to scientifically answering the above questions. And we can provide reasonable policy suggestions for the control of haze pollution.

Urban spatial form refers to the spatial pattern of urban elements in the spatial plane and vertical height direction, which is mainly reflected by the spatial heterogeneity caused by the overall shape of the city, land-use diversity, and urban density (Anderson et al. 1996). In fact, urbanization is not only manifested as population agglomeration or urban sprawl (Davis and Henderson 2003). The resulting population agglomeration, economic agglomeration, and land expansion will also affect the changes in the spatial form of various elements of the city. China's rapid industrialization and urbanization are the main causes of air pollution (Tao et al. 2015), so does the urban form have an impact on smog pollution? If there is an effect, what is the transmission mechanism behind it? And existing research has found that fragmented and complex-shaped urban forms produce more air pollution than compact cities with high continuity, low expansion, and low shape complexity (Li and Zhou 2019). In addition, with the urban expansion, the urban form gradually develops toward a high-density and compact model. This further absorbs resources such as human resources, capital, science and technology, medical care, and education into specific regions, providing development space and production factors for manufacturing agglomeration (Shao et al. 2019). Thus, it has led to a large number of manufacturing enterprises rapidly gathering in the city, forming manufacturing bases and industrial clusters, which drives China's regional economic development. But the large amount of energy consumed by resource-intensive and labor-intensive manufacturing is also a major cause of environmental pollution (Wang et al. 2019). Based on the above analysis, the urban form may have a moderating effect between manufacturing agglomeration and haze pollution. With the change of city forms, there may be a threshold effect between manufacturing agglomeration and haze pollution. Therefore, this study will explore the influence mechanism of the above two effects.

In conclusion, this paper uses Chinese urban panel data from 2006 to 2016 as a research sample. We then calculate the manufacturing agglomeration level of 283 Chinese prefecture-level cities and characterize the degree of haze pollution using PM2.5 concentration from satellite monitoring. In addition, Cities are important carriers of a country's economic development, which gather capital, labor, information, and other factors of production. Thus, the scale effect, agglomeration effect, and diffusion effect of cities in the development process significantly impact manufacturing and environmental pollution. Meanwhile, urban spatial form affects the distribution pattern of population and economic factors in the spatial dimension. And it has an important impact on urban economic activities. In particular, the urban form also reflects the current situation of urban land use, urban expansion, and urban development density. Therefore, whether the urban form develops in a proper and orderly direction is the key to whether the city can achieve sustainable development.

Based on the above analysis, previous studies seldom consider the impact of urban form on economic activities. And the urban form can affect manufacturing agglomeration and haze pollution by affecting land use and urban spatial structure patterns. Therefore, this paper introduces urban form into the analysis framework of manufacturing agglomeration and haze pollution, and quantifies urban form based on urban external shape complexity, compactness, and fragmentation. And we use the moderation effect model and the threshold regression model to examine the possible moderating effects and threshold characteristics of urban form between manufacturing agglomeration and haze pollution. This provides a scientific idea and method for the measurement of urban form and identifies the impact mechanism of urban form between manufacturing agglomeration and haze pollution.

Literature review and theoretical hypotheses

The theory of externalities suggests that industrial agglomeration has positive and negative externalities. And its combined results determine the environmental effects of industrial agglomeration (Porter 1990). The first type of research believes that manufacturing agglomeration will aggravate ecological pollution, and its mechanism is manifested in three aspects: (1) Crowding effect. When a large number of enterprises or labor are concentrated in a certain area, it will cause excessive consumption of resources and cause traffic congestion, which will significantly increase environmental pollution (Henderson 2003). At the same time, excessive industrial agglomeration may lead to vicious competition in the market for labor, technology, and commodities, which increases the production cost of enterprises and reduces their profits (Martin and Sunley 2006). The increase in cost minimizes the capital investment of enterprises in technological innovation of pollution treatment. And the decrease in profit leads to the lack of enthusiasm of enterprises to carry out technological innovation. Therefore, excessive industrial agglomeration inhibits the technological innovation of enterprises, which is not helpful in reducing haze pollution. (2) Industrial structure effect. In the preliminary phase of manufacturing agglomeration, the industrial structure is usually transformed into a "pollution-intensive" direction, resulting in increased energy consumption and pollutant emissions (Chen et al. 2019). (3) Downward competition effect. In order to attract enterprises to invest and drive local economic development, local governments compete to lower the environmental access threshold. The companies that entered at this time brought relatively low-level industries and technologies. As a result, the region falls into a vicious circle of "high energy consumption, high pollution" industrial agglomeration, resulting in increased emissions (List and Co 2000).

The second type of study argues that manufacturing agglomeration can improve environmental pollution and that its mechanism of action is manifested in three main ways: (1) Economies of scale effect. Agglomeration of manufacturing industries motivates the accumulation of capital, information, labor, and other factors of production in the aggregation area, which improves the effectiveness of resource distribution and production. The resulting economies of scale are conducive to forming a synergy of centralized production and pollution control, thereby reducing the cost of pollution control for enterprises (Meng and Xu, 2022). (2) Sharing effect. On the one hand, manufacturing enterprises concentrate their production activities in one region so that enterprises can share labor in this area. This helps companies select labor that matches high-level pollution technologies flexibly and improves their pollution treatment technology (Fang et al. 2020). On the other hand, regions with a high concentration of manufacturing industries also have more complete facilities and equipment. Enterprises can improve the pollution control level of the whole region by sharing energy-saving and emission reduction facilities (Helsley and Strange 1990). (3) Learning effect. Manufacturing agglomeration can promote information exchange between enterprises. In this way, it is helpful for the sharing and spillover of pollution control experience and pollution treatment technology (Glaeser et al. 1992), thereby alleviating the environmental pollution.

To sum up, the "cluster life cycle" theory believes that manufacturing agglomeration has the characteristics of stages (Ingstrup and Damgaard 2013). In the early stages of the development of manufacturing agglomeration. Enterprises seeking to maximize their interests may expand their production scale. At this time, the energy consumption is accelerated, and the crowding effect may be generated due to excessive agglomeration. In addition, the government has adopted relatively lax environmental regulation standards to attract investment, causing many polluting enterprises to move in, thus causing environmental pollution problems. However, when the level of manufacturing agglomeration reaches a certain threshold. The resource allocation in the manufacturing agglomeration area reaches the optimal state. At this time, the economies of scale of agglomeration are prominent, thereby reducing environmental pollution. Therefore, manufacturing agglomeration is characterized by different externalities at different stages. And the impact of various externalities on environmental pollution is quite different. At the same time, there are vast variations in economic development, government policies, and levels of marketization across China's regions. As a result, there may also be heterogeneity in manufacturing agglomeration and the stage of manufacturing development in different areas. According to the above viewpoints, we think that the agglomeration of manufacturing industries on haze pollution may show an inverted U-shaped of "promoting first and then inhibiting." And this relationship varies across regions. Therefore, we propose the following two hypotheses.

Hypothesis 1. The influence of manufacturing agglomeration on haze pollution has a nonlinear inverted "U" curve relationship.

Hypothesis 2. The impact of manufacturing agglomeration on haze pollution is heterogeneous in different regions of China.

This study believes that urban spatial form should comprehensively consider cities' compactness, density, and external shape characteristics in development (Fortuna et al. 2006).

(1) Urban exterior shape complexity. The external shape complexity of the city represents the degree of connectivity of each patch in the city. And the high complexity refers to severe segmentation among urban patches with low connectivity and accessibility (McCarty and Kaza 2015). On the one hand, complex urban boundaries may undermine the mobility of factors in production between regions, such as labor and capital. This leads to the less efficient allocation of resources and higher communication costs between enterprises (Ma et al. 2015). On the other hand, in the expansion process, the city may present a complicated external shape due to the influence of natural conditions such as mountains and hills. This can result in poor urban ventilation, which is detrimental to the dispersion of pollutants and enhances urban environmental pollution (Sha et al. 2018). Accordingly, the expansion of output scale resulting from manufacturing agglomeration has intensified the consumption of resources and energy. This process will lead to an increase in pollution emissions. In addition, complex urban boundaries are not conducive to the diffusion of pollutants, thus intensifying the negative externalities of manufacturing agglomeration on the environment.

(2) Urban compactness. Urban compactness refers to high-density agglomeration structures that maximize urban economic benefits. It emphasizes the "mixing of land use functions" under the high-intensity land use development model (Neuman 2005). One view holds that the increase in urban compactness helps to exert the inhibitory influence of the agglomeration of manufacturing on haze pollution. And the compactness of cities strengthens the intensity of urban land use. It is conducive to the agglomeration of construction land in the city, forming economies of scale (Brülhart and Sbergami 2009), thereby attracting manufacturing enterprises to agglomerate. At the same time, high-density urban development can prevent the blind expansion of urban construction land. It is beneficial to protect the grasslands, rivers, and other lands outside the city. It plays the role of greening the environment and absorbing pollutants (Banzhaf and Walsh 2008), which can effectively alleviate haze pollution. Another view is that the development of urban compactness exacerbates the negative influence of the agglomeration of manufacturing on environmental pollution. Within a fixed urban area, increasing compactness may increase urban land prices and labor costs (Gaigné et al. 2012). Manufacturing companies have scattered to the suburbs in pursuit of lower land and wage costs. And industrial suburbanization will weaken the economic "agglomeration effect," resulting in higher commuting costs and transportation costs, which will lead to increased pollutant emissions (Henderson 2003). At the same time, it is difficult for manufacturing enterprises to exert the positive effects of agglomeration, such as technology spillover, centralized treatment of pollutants, and industrial structure upgrading, thereby further aggravating environmental pollution (Zhao et al. 2022).

(3) Urban fragmentation. In the process of urban development, the urban form shows the characteristics of fragmentation in order to protect natural spaces such as rivers, grasslands, and forests (Wang et al. 2020). One view is that urban fragmentation exacerbates the negative effects of the concentration of manufacturing on environmental pollution. Urbanization is the primary driver of land fragmentation in China (Zhou et al. 2021). In the urbanization process, urban spaces that are not suitable for development and living may appear, such as parks, nature reserves, or industrial parks developed across regions (Wang et al. 2020). As a result, it is difficult for

manufacturing enterprises to form agglomeration economic advantages. The optimal allocation of production factors cannot be achieved, thus inhibiting the level of manufacturing agglomeration (Glaeser and Kahn 2010). Another view is that urban fragmentation helps to exert the inhibitory effect of manufacturing agglomeration on air pollution. The increase in urban fragmentation of cities will promote the transformation of cities from single-center to multi-center. The formation of polycentric cities is conducive to guiding manufacturing enterprises to transfer to sub-central cities. This can effectively alleviate the congestion effect and environmental pollution problems in central cities (Kloosterman and Lambregts 2001). In addition, the fragmentation caused by the increase of natural space can improve the ecological quality of the city. It is conducive to enhancing the city's attractiveness, promoting the city's agglomeration effect and economies of scale, thereby enhancing the level of manufacturing agglomeration (Banzhaf and Walsh 2008). Therefore, the development of urban fragmentation can reduce the crowding effect of central cities and promote the improvement of air quality. This can play the role of various positive externalities of manufacturing agglomeration to reduce haze pollution, thus forming a virtuous circle of improving the local ecological environment.

In summary, in the context of the rapid development of manufacturing, one view holds that the compact, fragmented and complex development of urban forms will lead to a decline in the level of manufacturing agglomeration. Under such circumstances, it is difficult to take advantage of the positive externalities such as economies of scale, technology spillovers, circular economy, and labor sharing of manufacturing agglomeration, thereby aggravating haze pollution. Another view is that changes in urban form can directly improve the level of manufacturing agglomeration. On the other hand, it can also form a positive feedback effect on manufacturing agglomeration through environmental improvement. This can bring about the mitigation effect of manufacturing agglomeration on haze pollution. In addition, when the complexity of the external shape of the city and the degree of urban fragmentation is low, its impact on manufacturing agglomeration is relatively tiny. At this time, manufacturing agglomeration can play various positive externalities to reduce the level of haze pollution. But with the increase in the complexity of the external shape and the fragmentation of the city, manufacturing agglomeration has been suppressed. And the crowding effect of manufacturing agglomeration is greater than the effect of economies of scale, thus showing a promoting effect on haze pollution. When urban compactness is low, disordered, low-density urban sprawl can negatively impact economic development. It will not only lead to inefficient allocation of production factors but also weaken the ability of cities to divide labor and cooperate, resulting in increased production costs and transaction costs. The increase in cost will inhibit the agglomeration effect and scale economy effect of manufacturing enterprises, thereby aggravating the haze pollution. However, when the level of urban compactness reaches a certain level. Various positive effects of manufacturing agglomeration gradually become dominant, significantly reducing haze pollution. Therefore, due to the different development stages of different urban forms in terms of scale, structure, and shape. The effect of aggregation of manufacturing industries on haze pollution may also be quite different in different urban forms. This implies that there may be a threshold effect between manufacturing agglomeration and haze pollution under the effect of urban form. Based on the above analysis, we propose hypothesis 3 and hypothesis 4:

Hypothesis 3. The urban form has a moderating effect on the relationship between manufacturing agglomeration and haze pollution.

Hypothesis 4. Under the influence of urban form, the impact of manufacturing agglomeration on haze pollution presents threshold characteristics.

Methodology

Spatial Econometric Models

In this research, the existence of spatial dispersion of pollutants is considered. The haze pollution in a region mainly comprises the actual generation of haze pollution in the area and the diffusion amount from other regions (Sun et al. 2014). And part of the real production of smog pollution in this region will spread to other areas. This part does not affect local haze pollution, so we subtract it (Shao et al. 2016). And the diffusion of haze pollution from other areas and the dispersal of the region to other areas reflect the spatial dependence of haze pollution in each region (Yang et al. 2021). Based on this, this study will establish spatial econometric models. And we introduce the squared term of manufacturing agglomeration (*sMan*) to investigate the nonlinear relationship between manufacturing agglomeration and haze pollution. There are three forms of spatial econometric models: The Spatial Autoregressive Model (SAR) is mainly applied to investigate the spatial dependency characteristics between explained variables. The Spatial Error Model (SEM) is used to research the spatial association of omitted variables or unobservable random shocks not included in the explanatory variables. And the Spatial Durbin Model (SDM) takes into account the situation where both spatial lag and spatial error may exist simultaneously. Since SAR and SEM are more specific than general-purpose SDM, this paper will focus on examining the applicability of SAR and SEM to explore the spatial effect of the agglomeration of manufacturing on haze pollution and its transmission mechanism. The two models mentioned above are represented as follows:

$$PM_{\mathrm{it}} = \alpha_0 Man_{it} + \alpha_1 sMan_{it} + \alpha_2 X_{it} + \rho \sum\nolimits_{\mathrm{j}} w_{ij} PM_{jt} + \mathrm{u}_{it} \tag{1}$$

$$PM_{\mathrm{it}} = \beta_0 Man_{it} + \beta_1 sMan_{it} + \beta_2 X_{it} + \beta_3 \mu_{it} + \lambda \sum\nolimits_{j} w_{\mathrm{ij}} \mu_{it} + \phi_{it} \tag{2}$$

In this paper, *PM* is used to denote the explanatory variable, haze pollution; *Man* is the core explanatory variable of this paper, manufacturing agglomeration; *sMan* is the squared term of manufacturing agglomeration; *X* represents the vector composed of control variables, and α and β are their corresponding coefficient vectors; $\varphi_{it} = \varepsilon_{it} + u_{it}$, ε_{it} and u_{it} both conform to the disturbance term of the normal distribution; The current period spatial lag coefficient is denoted by ρ, and the current spatial error term coefficient is denoted by λ.

Spatial econometric model based on moderating effect

To examine whether manufacturing agglomeration affects haze pollution through urban form, we introduce the urban form (*Cform*) into the spatial measurement model and establish the following moderating effect model, as shown in formulas (3)-(4):

$$PM_{\mathrm{it}} = \alpha_0 Man_{it} + \alpha_1 sMan_{it} + \alpha_2 Man_{it} \times Cform_{it} + \alpha_3 sMan_{it} \times Cform_{it} + \alpha_4 X_{it} + \rho \sum\nolimits_{\mathrm{j}} w_{ij} PM_{jt} + \mathrm{u}_{it} \tag{3}$$

$$PM_{\mathrm{it}} = \beta_0 Man_{it} + \beta_1 sMan_{it} + \beta_2 Man_{it} \times Cform_{it} + \beta_3 sMan_{it} \times Cform_{it} + \beta_4 X_{it} + \beta_5 \mu_{it} + \lambda \sum\nolimits_{j} w_{\mathrm{ij}} \mu_{it} + \phi_{it} \tag{4}$$

Establishment of threshold regression model

The basic idea of the threshold regression model is that when an explanatory variable is in a different range, it has a significantly different effect on the explained variable (Hansen 1999). To test the threshold effect of urban form (*Cform*) between haze pollution and manufacturing agglomeration, we first set a single threshold regression model, which can be expressed as:

$$PM_{it} = \alpha X_{it} + \beta_1 Man_{it} \times I(Cfrom_{it} \leq \delta_1) + \beta_2 Man_{it} \times I(Cfrom_{it} > \delta_1) + C + \varepsilon_{it} \tag{5}$$

In formula (5), *PM* is chosen to represent the explanatory variables, and *X* is composed of control variables, *Cfrom* represents the threshold variable urban form, δ represents a fixed threshold value, α is the coefficient of the effect of control variables on the explanatory variable, $\beta 1$ and $\beta 2$ represent the influence coefficients of manufacturing agglomeration on haze pollution under different threshold levels, the constant term is *C*, $\varepsilon_{it} \sim (0, \sigma^2)$ means a random disturbance term, and $I(\cdot)$ is an indicator function. Similarly, the formulas of the double threshold test and the triple threshold test that we set up are as follows. Accordingly, the meanings of $\beta 3$ and $\beta 4$ are analogous to that of $\beta 1$.

$$PM_{it} = \alpha X_{it} + \beta_1 Man_{it} \times I(Cfrom_{it} \leq \delta_1) + \beta_2 Man_{it} \times I(\delta_1 < Cfrom_{it} \leq \delta_2) + \beta_3 Man_{it} \times I(\delta_2 < Cfrom_{it} \leq \delta_3) + C + \varepsilon_{it} \tag{6}$$

$$PM_{it} = \alpha X_{it} + \beta_1 Man_{it} \times I(Cfrom_{it} \leq \delta_1) + \beta_2 Man_{it} \times I(\delta_1 < Cfrom_{it} \leq \delta_2) + \beta_3 Man_{it} \times I(\delta_2 < Cfrom_{it} \leq \delta_3) + \beta_4 Man_{it} \times I(\delta_3 < Cfrom_{it} \leq \delta_4) + C + \varepsilon_{it} \tag{7}$$

Data description

Dependent variable: PM2.5 (*PM*)

PM2.5 is considered to be the main component of haze pollution in China. It has a significant adverse influence on air quality, residents' health, and economic sustainability (Zhu et al. 2019). Based on this, we use the annual average concentration of PM2.5 to characterize the urban haze pollution level. The data in this article are from raster data published by the Center for Socioeconomic Data and Applications at Columbia University (van Donker et al. 2015). Then we use ArcGIS software further to parse the annual average PM2. 5 concentration data.

Figure 1 shows the variation of haze pollution in eastern, central, and western regions of China. And urban air pollution in China shows a fluctuating downward trend. The concentration of PM2.5 dropped from 46.74ug/m3 in 2006 to 37.81ug/m3 in 2016. However, it is still significantly higher than the national PM2.5 secondary concentration limit (35). The central region has the highest air pollution in sub-regions, followed by the eastern part. Air pollution in both areas is higher than the national average. And haze pollution concentration in the western area is below the national average. Although the west region was lower than the national second-level limit (35) for PM2.5 in 2011, 2012, 2015, and 2016, it was higher than the second-level limit in other years. Therefore, there is a certain degree of haze pollution in all country regions.

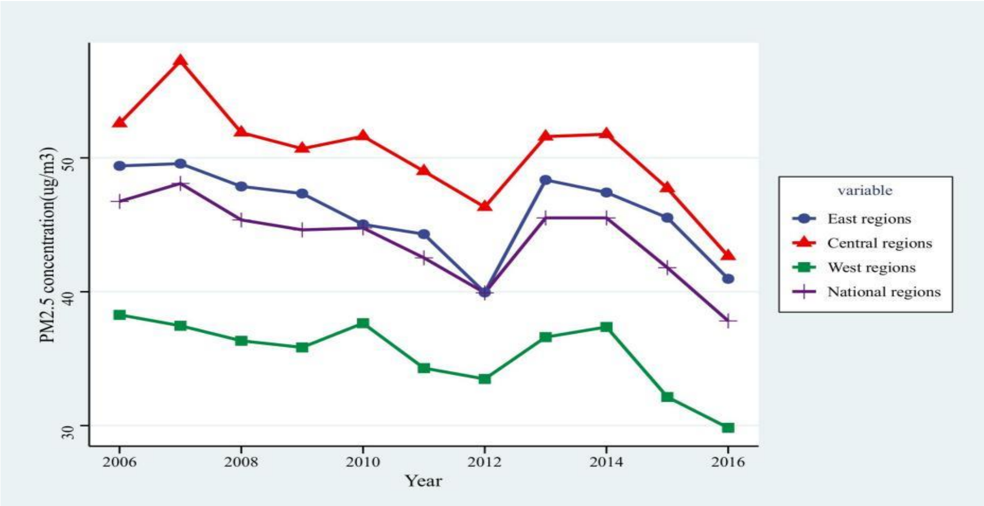

Fig. 1 The changes of haze pollution in three regions

Independent variable: Manufacturing agglomeration (*Man*)

In this paper, we refer to the method of O'Donoghue and Gleave (2004) and measure the agglomeration level with the location entropy. This indicator is simple and easy to implement. And it can accurately reflect the comparative advantages of the national urban manufacturing agglomeration, which can better eliminate the endogenous effects of different regional scales. The formula for calculating the location entropy of industry *i* in region *j* is as follows:

$$MAN = \frac{x_{ij} / x_j}{x_i / x} \tag{8}$$

In the formula, x_{ij} is the number of employed persons of industry i in area j, x_j is the number of employed persons of all industries in area j, x_i is the employment in the industry i at the national level, and x is the employment in all industries at the national level.

Moderating Variables and Threshold Variables: Urban Form (*Cfrom*)

Urban exterior shape complexity (*FD*). The urban spatial form has irregularity and self-similarity. Fractal dimension (*FD*) quantifies the irregularity and self-similarity of the urban spatial form (Frankhauser 2015; Terzi and Kaya 2011). *FD* will increase if cities become irregular and have uneven boundaries as they expand. Therefore, we use *FD* to characterize the urban land shape complexity.

Urban compactness (*LPI*). Compact cities are becoming the direction of urbanization. It represents a model of urban construction and spatial development layout with high density and efficient mixed land use (Xu et al. 2017). In this paper, the largest patch index (*LPI*) is introduced into the model to characterize the level of urban compactness. The calculation method is the proportion of the largest urban land patch in the total urban land area.

Urban Fragmentation (*PD*). Fragmentation can be quantitatively analyzed by patch density, which can better characterize the degree of urban leapfrog development (Bechle et al. 2011). We use the number of fragmented urban patches and the ratio of the total urban area for the calculation.

Control variables

On the basis of referring to the existing research, we introduce the following control variables to reduce the influence of missing variables on the regression results.

(1) Transportation (*Tra*). The number of road kilometers (Km) is used to measure the city's transportation intensity. The long-term growth rate of the road is lower than the growth rate of the vehicle will increase the traffic flow on the road, which is easy cause slow traffic flow and even traffic congestion. And this leads to inefficient combustion of vehicle fuels, which largely contributes to air pollution in cities (Wrobel et al. 2000).

(2) Open level (*Open*). International knowledge transfer and emission reduction technologies brought by foreign investment can effectively enhance the confidence and ability of host countries to control haze (Gao et al. 2017). Thus, we use foreign direct investment (10^3 yuan) to characterize the city's openness level.

(3) Population density (*Pop*). Overpopulation can have a crowding effect. It will not only increase the consumption of resources and energy but also cause a series of urban problems such as traffic congestion, which will cause the urban environment to deteriorate (Li et al. 2021). In this paper, the number of people per unit of the urban area is used to measure the effect of urban population concentration on haze pollution.

(4) Energy consumption structure (*Es*). Pollutants generated by high-intensity energy consumption are the main cause of haze pollution (Kouchak-Penchah et al. 2016). To control the impact of energy consumption on smog pollution, this paper measures energy consumption using the share of coal consumption in total energy consumption.

(5) Technical level (*Tec*). Technological innovation can reduce energy consumption and emission reduction costs by improving energy efficiency in the production process (Sohag et al. 2015). In the long run, technological progress has a suppressing effect on haze pollution. Therefore, we use the number of three patent applications (pieces) to reflect the technical level of the city.

(6) Environmental regulation (*Er*). Environmental regulation will inhibit the pollutant discharge behavior of enterprises. At the same time, excessive ecological regulations will force companies to relocate, thereby reducing environmental pollution associated with economic growth (Shapiro and Walker 2018). Thus, we introduce the proportion of environmental protection expenditure in GDP into the study to examine the effect of environmental regulation intensity on haze pollution.

Spatial weight matrix

Geographical closeness and economic relationship are essential factors affecting the spatial layout of manufacturing and haze pollution. Therefore, the setting of the weight matrix needs to consider the effects of geographic distance and economic connection. Based on this, this paper constructs a city-based geographic distance spatial matrix (W1). And element w_{ij} denotes the number of nearest road miles between city i and j. In addition, to verify the results of the robustness of the spatial distance weight matrix selection, we also construct an economic distance weight matrix (W2) for robustness testing.

Data Sources

This paper takes into account data availability and references to existing literature. And we have made the following choices for the variables mentioned in the paper.

Table 1 Data selection and description

Variable type	Indicator selection	Variable name	Indicator description	Data source
Dependent variable	Haze pollution	*PM*	Annual average concentration of PM2.5	Columbia University International Geoscience Information Network (https://beta.sedac.ciesin.columbia.edu/)
Independent variable	Manufacturing agglomeration	*Man*	Manufacturing agglomeration level	Formula (8) calculates
Control variable	Transportation	*Tra*	City road kilometers	China Urban Statistical Yearbook (2007-2017)
	Open level	*Open*	FDI	
	Population density	*Pop*	Population/Regional administrative area	
	Energy consumption structure	*Es*	Total coal consumption/Total energy consumption	
	Technical level	*Tec*	The number of three patent applications	
	Environmental regulation	*Er*	Environmental expenditure/GDP	
Moderating variables and threshold variables	Urban exterior shape complexity	*FD*	Fractal dimension calculation	ESA Global Land Cover Information Database (2007-2017)
	Urban compactness	*LPI*	Largest urban land patch/total urban land area	
	Urban fragmentation	*PD*	Number of urban patches/total urban land area	

Empirical regression results and discussion

Selection of model forms

Before estimating model parameters, the Lagrange multiplier (LM) test determines whether to select SAR or SEM for analysis. The judging criteria are: if the LM statistic and the robust LM statistic of the SEM are significant, the SEM is selected. And the SAR is chosen if both the LM statistic and the robust LM statistic of the SAR are significant (Elhorst et al. 2014). The results of the test are shown in Table 2, and SAR is the more appropriate model under the setting of geographic distance spatial weight matrix (W1) and economic distance weight (W2).

Table 2 Lagrange multiplier test of spatial model

	W1		W2	
	χ^2	P-Value	χ^2	P-Value
Lagrange multiplier-lag	136.619	0.000	139.021	0.000
Lagrange multiplier-error	176.407	0.000	188.120	0.000
Lagrange multiplier-lag-Robust	19.093	0.000	20.482	0.000
Lagrange multiplier-error-Robust	7.309	0.203	8.890	0.198

Spatial econometric regression model results

Table 3 shows the regression results of manufacturing agglomeration on haze pollution by OLS, OLS-FE, SAR, and SEM. The estimated coefficients of manufacturing agglomeration in M1 and M2 without considering the spatial correlation are not significant. Therefore, not considering spatial correlation may get biased estimation results.. The estimation results of M3 and M4, considering the spatial correlation, show better statistical characteristics. Further from the comparison between M3 and M4, since R^2 in M3 is slightly higher than in M4, it proves that the SAR fits the sample data better than the SEM.

Table 3 Spatial econometric model regression results

Variable	OLS	OLS-FE	SAR	SEM
	M1	M2	M3	M4
Man	0.4684	0.0138	0.0958***	0.0966***
	(1.10)	(0.83)	(3.28)	(3.30)
sMan	-0.0082	-0.0070*	-0.0414***	-0.0415***
	(-0.34)	(-1.67)	(-4.20)	(-4.20)
lnTra	-0.0867	-0.0214***	0.0855***	0.0852***
	(-1.26)	(-4.02)	(8.53)	(8.47)
lnOpen	-0.0275	0.0073	0.0273**	0.0277**
	(-1.06)	(1.05)	(2.36)	(2.39)
lnPop	4.2572***	-0.0245	0.3838***	0.3851***
	(3.66)	(-1.56)	(44.61)	(44.82)
lnEs	-0.1388	0.0039	-0.0535***	-0.0534***
	(-1.12)	(0.54)	(-6.58)	(-6.56)
lnTec	-0.0287	-0.0433***	-0.0139*	-0.0141*
	(-0.75)	(-11.17)	(-1.79)	(-1.82)
lnEr	-0.1867	0.0065	0.0810***	0.0819***
	(-1.11)	(0.98)	(5.52)	(5.57)
Rho			-0.4423**	-0.8758**
			(-2.06)	(-2.44)
R^2	0.3326	0.2001	0.5562	0.5529
Obs	3113	3113	3113	3113

Note:*, ** and *** indicate 10%, 5% and 1% significance levels respectively. The following tables are identical.

According to the regression results, the spatial lag term coefficient in Modle3 is significant at the 5% level. It shows an apparent spatial correlation feature of urban haze pollution in China. On the one hand, under the dual effects of natural reasons such as atmospheric circulation and water flow and economic activities such as regional economic integration and regional industrial transfer, geographical proximity is strongly correlated with the level of haze pollution. This suggests the necessity for strengthening regional cooperation in the fight against haze pollution. Otherwise, it will significantly undermine the level of regional haze control. On the other hand, there are strategic interactions between local governments in environmental regulation. And the haze control effect of environmental regulations in neighboring areas can affect the haze pollution concentration in the region through haze pollution spillover. In addition, the regional haze pollution control model and successful experience will also form a strong demonstration effect on neighboring regions through information exchange and technology spillover.

The primary term for manufacturing agglomeration is significantly positive at 1%. And the squared term of manufacturing agglomeration is highly negative at 1%. This implies that manufacturing agglomeration has a significant inverted "U" curve relationship with haze pollution. When manufacturing agglomeration is in its infancy, it has a significantly aggravating influence on the pollution of haze. But with the improvement of the agglomeration level of the manufacturing industry, the positive externality of manufacturing agglomeration has gradually become prominent, thus showing a suppression effect on haze pollution. The initial stage of the agglomeration of the manufacturing industry usually indicates the characteristics of rigid energy demand and rapid growth of energy consumption. At this time, the pollution emission effect brought by the concentration of manufacturing industries is greater than the economy of scale effect and knowledge spillover effect. Therefore, the rapidly advancing manufacturing agglomeration is usually accompanied by an extensive economic growth model of higher energy consumption and emissions, which leads to frequent haze pollution problems. When the level of manufacturing agglomeration reaches a certain threshold, the positive externalities such as resource-saving and sharing effect of manufacturing agglomeration are gradually becoming more prominent. At this time, the aggregation of manufacturing industries began to show a suppressing effect on haze pollution. The reason is that the concentration of manufacturing industries is conducive to enterprises sharing energy-saving and emission-reduction treatment facilities or technologies. This can reduce the level of haze pollution. In addition, the unit cost of government regulation of pollutant emissions will be lower due to the spatial concentration of manufacturing.

The control variable results in Table 3 show: that for every 1% increase in transportation volume, the haze pollution intensity will increase by 0.0855%. This indicates that the expansion of China's transportation scale in recent years has promoted haze pollution. The opening level shows an increasing effect on haze pollution at the 5% significance level, which supports the "pollution paradise" hypothesis of China's haze pollution was established. The influence of population density on haze pollution is positive and significant. It means that the increase in population density will generate a large amount of energy and transport demand, thus increasing haze pollution. The energy consumption structure exhibits a significant effect on decreasing haze pollution, which indicates that the "green" upgrade of the energy consumption structure being promoted in China helps mitigate haze pollution. And the level of technology has a significantly negative impact on haze pollution. It shows that technological innovation can reduce pollution emissions, thereby inhibiting haze pollution. Environmental regulation shows a significant promoting influence on haze pollution. The reason is that local governments have adopted relatively lax environmental regulation standards to promote economic development. And this method will attract a lot of polluting firms to invest, making the place a "pollution sanctuary," thus aggravating smog pollution.

Robustness tests

In this paper, we mainly select four methods: replace space weight matrix, replace model, use dynamic space measurement model and replace variable calculation method to test the robustness of the regression results of the spatial measurement model. The specific process is as follows: First, we choose the economic distance matrix (W2) to substitute the geographic distance space weight matrix (W1) previously used in the regressions for robustness testing. Secondly, based on the GS2SLS model, this study uses the spatial lag term as an instrumental variable. The model is re-estimated based on W1, and the endogeneity of the model is tested. Third, re-estimate based on dynamic SAR, replacing the previously used first-order spatial lag term in the regression as the explanatory variable. Finally, the calculation method of manufacturing agglomeration is changed. And the spatial Gini coefficient is used to calculate the level of urban manufacturing agglomeration. Table 4 is the result of the robustness test regression. The spatial lag term of haze pollution remains significant. And the global Moran index reported by GS2SLS is also still substantial. In addition, the impact of manufacturing agglomeration on haze pollution shows an inverted "U" shape relationship. The above results show that the previous benchmark regression has strong robustness and once again verifies that hypothesis 1 is established.

Table 4 Robustness test regression results

Variable	Replace weight M1	Replace model M2	Dynamic SAR M3	Replace variable M4
$W*PM_{t-1}$		1.1738***	1.2303***	
		(20.34)	(15.50)	
Man	0.0870***	0.0865***	0.1023***	0.0870***
	(2.99)	(2.93)	(3.67)	(3.45)
sMan	-0.0403***	-0.0393***	-0.0523***	-0.0349**
	(-3.34)	(-3.94)	(-4.34)	(-3.70)
lnTra	0.0870***	0.0824***	0.0902***	0.0768***
	(7.32)	(8.14)	(9.23)	(4.58)
lnOpen	0.0378**	0.0295**	0.0302***	0.0309**
	(2.09)	(2.52)	(2.76)	(2.01)
lnPop	0.3046**	0.3864***	0.4034***	0.3793***
	(2.23)	(44.48)	(56.88)	(50.81)
lnEs	-0.0459**	-0.0472***	-0.0403***	-0.0308***
	(2.04)	(-5.69)	(-6.77)	(-3.34)
lnTec	-0.0023*	-0.0159**	-0.0209*	-0.106*
	(-1.77)	(-2.02)	(-1.84)	(-1.67)
lnEr	0.0285***	0.0850***	0.1102***	0.0780***
	(4.08)	(5.75)	(6.54)	(7.02)
Global Moran		1.2033***		

index		(6.90)		
Rho	0.6709**	1.0834***	1.2403**	1.0348**
	(2.34)	(15.80)	(27.98)	(25.04)
R^2	0.5067	0.5219	0.9560	0.5672
Obs	3113	3113	3113	3113

Different regional tests

According to the regression results in Table 5, the agglomeration of manufacturing industries in the eastern and central regions has a significant inverted U-shaped effect on haze pollution. In contrast, manufacturing agglomeration in the west does not have a significantly impact on haze pollution. Thus, it shows that there are regional differences in the impact of the concentration of manufacturing industries on haze pollution in China. First of all, the eastern and central regions not only have abundant human capital but also have better conditions in terms of openness and infrastructure, which attract a large concentration of manufacturing enterprises. In the stage of rapid development of the manufacturing industry, energy consumption usually increases rapidly, and the manufacturing industry at this time has the characteristics of high pollution and high energy consumption. And the government adopts relatively lax environmental regulation standards to promote rapid economic development during this period. This causes manufacturing enterprises to ignore the investment in green technology innovation in the production process and attracts a large number of highly polluting enterprises to move in. As a result, the agglomeration of manufacturing industries exacerbates haze pollution. However, with the increasingly prominent negative externalities of manufacturing agglomeration, the government gradually realizes the importance of the ecological environment. And at this stage, they began to implement strict environmental regulation policies, forcing enterprises to invest more in green technology innovation. In addition, the positive impact of the industrial structure upgrading effect and technology spillover effect of manufacturing agglomeration during this period also began to dominate, thus significantly reducing the problem of haze pollution. Secondly, the primary coefficient of manufacturing agglomeration in the eastern region is lower than in the central region. This may be due to the fact that in the economic development of the central region, it has undertaken many pollution-intensive industries from the east. At the same time, the development level of the manufacturing industry in the western region may not reach the carrying capacity of the environment, so the influence coefficient is not significant.

Table 5 Regional sample regression

Variable	Eastern region	Central region	Western region
	M1	M2	M3
Man	0.2358***	0.2509***	0.0114
	(2.88)	(4.04)	(0.21)
sMan	-0.0256**	-0.1350***	-0.0169
	(-1.92)	(-4.04)	(-0.63)
lnTra	0.2794***	-0.0286***	-0.0181**
	(13.63)	(-3.08)	(-2.20)
lnOpen	0.0201*	0.0179***	0.0236***

	(1.78)	(2.75)	(4.73)
lnPop	0.1849***	0.4199***	-0.0502*
	(8.13)	(45.10)	(-1.78)
lnEs	-0.0370*	-0.0492*	-0.0034
	(-1.80)	(-6.14)	(-0.25)
lnTec	-0.0341**	0.0094	-0.0234***
	(-2.27)	(1.25)	(-4.29)
lnEr	0.0730**	0.0796***	-0.0044
	(2.20)	(5.59)	(-0.44)
Rho	-0.5188*	-0.0221**	0.7504***
	(-1.82)	(-2.42)	(17.31)
R^2	0.2328	0.7509	0.6597
Obs	1111	1100	902

Moderating effect regression results

Table 6 reports the moderating effect of urban form on the relationship between manufacturing agglomeration and haze pollution. In model (1), the interaction coefficient between the complexity of urban exterior shape and manufacturing agglomeration is positively significant at 5%. This means that as the external shape of the city develops in a complex way, it positively moderates the relationship between manufacturing agglomeration and haze pollution. And the concentration of manufacturing industries will further aggravate haze pollution. The product term coefficient of the external shape complexity of the city and the squared term of manufacturing agglomeration is negative and insignificant. This shows that when the manufacturing agglomeration level is on the right side of the inverted U-shaped curve, the urban exterior shape complexity has no moderating effect on the relationship between the agglomeration of manufacturing and haze pollution. The reason is that, on the one hand, the complex development of urban boundaries may lead to traffic congestion and poor flow of production factors. This will increase the production cost of manufacturing enterprises, which is not conducive to improving the level of manufacturing agglomeration. At this time, it is difficult for manufacturing companies to exert the agglomeration effect on the mitigation of haze pollution. On the other hand, complicating urban boundaries can adversely affect the permeability of cities. This has led to the accumulation of many pollutants emitted by the manufacturing industry in the city, thus increasing haze pollution.

The interaction term between urban compactness and manufacturing agglomeration shows insignificant positive characteristics. And the interaction term of the urban compactness and the squared term of manufacturing agglomeration is not significant in a negative way. This demonstrates that compact urban form does not have a moderating effect on the concentration of manufacturing and haze pollution. The reason is that the increased compactness of the city is conducive to a higher level of manufacturing agglomeration. On the one hand, the participation of many industrial enterprises will have a siphon effect on energy consumption, thereby aggravating the local haze pollution level. However, increased urban compactness can also drive business and population agglomeration through compact land use and transportation. The agglomeration of production factors can promote the spillover effect of technology through sharing, matching, and learning mechanisms, thereby reducing haze pollution. Therefore, the compact development of urban form has simultaneously negative and positive externalities, and the two form a balanced development trend in the game process. This indicates that the moderating effect of urban form compactness on the agglomeration of manufacturing and haze pollution is not significant.

The interaction coefficient between urban fragmentation and manufacturing agglomeration is 2.9504, which is statistically significant and positive at the 1% level. This shows that increased urban fragmentation has a positive moderating effect between manufacturing agglomeration and haze pollution. Thus, manufacturing agglomeration will further intensify haze pollution. And the coefficient of the interaction term between urban fragmentation and the squared term of manufacturing agglomeration is -0.7113, which is quite negative. When the level of manufacturing agglomeration is on the right side of the inverted U-shaped curve, urban fragmentation has a negative moderating effect on the relationship between the agglomeration of manufacturing and haze pollution. And it is due to the fact that the development of land fragmentation will promote the formation of multiple central cities. The increase in urban polycentricity will make the distribution of regional resources more decentralized. It is difficult to form an urban agglomeration economy, which makes it difficult for manufacturing enterprises to create economies of scale, thus promoting haze pollution. In addition, many industrial zones developed across regions will cause the emission of pollutants, mainly including smoke and dust, which induce haze pollution. At the same time, China is currently in rapid industrialization and urbanization. The environmental improvement effect of natural spaces such as rivers and grasslands is insufficient to reduce pollution emissions from manufacturing agglomeration significantly.

Table 6 Moderating effect regression results

Variable	M1	M2	M3
Man	-1.9381** (-2.13)	-0.0303 (-0.47)	-0.2883*** (-4.70)
sMan	0.4917 (1.34)	-0.0018 (-0.07)	0.0487** (2.46)
*Man*FD*	1.1816** (2.22)		
*sMan*FD*	-0.3091 (-1.43)		
*Man*LPI*		0.2763 (1.52)	
*sMan*LPI*		-0.0947 (-1.39)	
*Man*PD*			2.9504*** (5.48)
*sMan*PD*			-0.7113*** (-3.02)
lnTra	0.0542*** (5.63)	0.0641*** (6.68)	0.0553*** (5.70)
lnOpen	-0.0377***	-0.0148	0.0058

	(-3.31)	(-1.32)	(0.53)
lnPop	0.3819***	0.3957***	0.3744***
	(47.00)	(48.10)	(45.46)
lnEs	-0.0156**	-0.0011	-0.0105
	(-1.97)	(-0.14)	(-1.30)
lnTec	0.0115	0.0049	0.0192**
	(1.56)	(0.66)	(2.54)
lnEr	0.0571***	0.0633***	0.0542***
	(4.11)	(4.53)	(3.87)
Rho	-0.2268	-0.2819	-0.3000
	(-1.14)	(-1.39)	(-1.48)
R^2	0.0960	0.0973	0.0976
Obs	3113	3113	3113

Threshold effect regression results

This paper uses Stata15.1 software to perform regression analysis on panel data. Under the Bootstrap method of repeated sampling 300 times, we get the test and calculation results through formula (5) and stata15.1 software.

According to Table 7, when three urban forms characterized by urban exterior shape complexity (*FD*), urban compactness (*LPI*), and urban fragmentation (*PD*) are threshold variables. This study concludes: that *FD*, *LPI*, and *PD* are significant at the 1% level, whether a single threshold test or a double threshold test. In addition, the double threshold F statistic value of the three urban forms is the largest. Therefore, this study adopts a double threshold for analysis.

Table 7 Threshold effect test

variable	*FD*	*LPI*	*PD*
Single threshold test	30.162***	14.894***	20.438***
	(0.000)	(0.000)	(0.000)
Double threshold test	311.307***	129.389***	352.152***
	(0.000)	(0.040)	(0.000)
Triple threshold test	7.020***	0.000	0.000
	(0.000)	(0.970)	(0.170)

Note: P statistic in parentheses. Above the parentheses are the F statistic.

Table 8 Estimated threshold

Threshold variable	Threshold estimate 1	95% confidence interval	Threshold estimate 2	95% confidence interval
FD	1.619	[1.619，1.703]	1.703	[0.169，0.704]
LPI	0.100	[0.093，0.100]	0.414	[0.408，0.517]
PD	0.050	[0.022，0.050]	0.077	[0.077，0.077]

Table 9 Threshold regression results

variable	*FD*	*LPI*	*PD*
lnTra	0.0267***	0.0114	0.0299***
	(3.41)	(1.32)	(3.52)
lnOpen	0.0111	-0.0020	0.0477***
	(1.08)	(-0.18)	(4.32)
lnPop	0.3984***	0.3423***	0.4013***
	(52.12)	(37.04)	(46.79)
lnEs	-0.0198***	0.0338***	-0.0072
	(-2.72)	3.81	(-0.91)
lnTec	-0.0601***	-0.0406***	-0.0445***
	(-10.32)	(-6.34)	(-7.07)
lnEr	0.0795***	0.0451***	0.0645***
	(5.78)	(2.91)	(3.40)
$Cfrom < \delta 1$	-0.3511***	0.2653***	-0.3402***
	(-11.97)	(10.19)	(-13.01)
$\delta 1 < Cfrom < \delta 2$	-0.0459***	0.1015***	-0.1574***
	(-3.00)	(7.20)	(-9.68)
$Cfrom > \delta 2$	0.0993***	-0.0490***	0.0571***
	(7.24)	(2.62)	(3.89)
Constant	1.3926***	1.5109***	0.9910***
	(23.47)	(22.18)	(13.95)
R^2	0.5756	0.6683	0.7062
Obs	3113	3113	3113

According to Table 9, the impact of urban exterior shape complexity (*FD*) on haze pollution has a significant double threshold feature. When *FD*<1.619, its influence coefficient on haze pollution is -0.3511; when 1.619<*FD*<1.703, the regression coefficient is -0.0459; when *FD*>1.703, its corresponding regression coefficient becomes 0.0993. And the above three regression coefficients are statistically significant at the 1% level. It follows that *FD*'s negative effect on haze pollution increases gradually with the complexity of the external shape of the city. When the threshold of 1.703 is crossed, *FD* shows a significant contribution to haze pollution. The reason is that the high complexity of construction land around the city will cause traffic congestion. And this will lead to slower vehicle speed and long driving time, which will accelerate exhaust emissions, resulting in severe haze pollution. In addition, the increase in *FD* will also cause poor communication between regions. It hinders companies from taking advantage of economies of scale through technology spillovers and sharing infrastructure, which is not beneficial in mitigating haze pollution. To sum up, the increase in the complexity of the external shape of the city will play a negative externality effect on aggravating the haze pollution.

The impact of urban compactness (*LPI*) on haze pollution has a significant double threshold feature. When *LPI*<0.100, the impact coefficient of *LPI* on haze pollution is 0.2653 and passes the test of significance at the 1%; The impact coefficient of *LPI* on haze pollution is 0.1015 when 0.100 < *LPI* < 0.414, and its effect is significantly promoted; When *LPI*>0.414, the regression coefficient of *LPI* on haze pollution becomes -0.0490 and is significant at the 1% level. In conclusion, the contribution of *LPI* to haze pollution shows a decreasing trend. When *LPI* crosses the second threshold, *LPI* positively impacts suppressing haze pollution. And the higher the *LPI* value, the more compact the urban spatial form is. On the one hand, the improvement of urban compactness is conducive to giving full play to the positive externalities such as the economies of scale of manufacturing agglomeration and the centralized treatment of pollution. This can effectively alleviate the problem of haze pollution. On the other hand, the diversified development models and convenient urban transportation of compact cities will strengthen innovative talents and enterprises' attractiveness. And diversified agglomerations arising from the diversification of land use will also contribute to the spillover effect of technology. Thus, increased urban compactness will reduce air pollutant emissions by improving urban technology levels.

Urban fragmentation (*PD*) has a significant double threshold characteristic for haze pollution. When $PD<0.050$, the influence coefficient of urban fragmentation on haze pollution is -0.3402; When $0.050<PD<0.077$, the influence coefficient of *PD* on haze pollution is -0.1574; when $PD>0.077$, the influence of *PD* on haze pollution changes from negative to positive, and the corresponding regression coefficient is 0.0571. The above three regression coefficients all pass the 1% significance test. To sum up, when the degree of urban fragmentation is in different ranges, its impact on haze pollution is quite different. When the urban fragmentation is low, *PD* positively affects haze pollution. However, as urban fragmentation develops, this positive effect has diminished. When the threshold value of 0.077 is crossed, the increase in *PD* will significantly promote haze pollution. When the urban fragmentation is low, manufacturing enterprises can play a positive externality role in the agglomeration effect. Specifically, improving the manufacturing agglomeration level is conducive to improving resource utilization efficiency, saving costs, and sharing pollution treatment facilities, thereby effectively reducing haze pollution. However, the fragmented development of urban form may inhibit the increase in manufacturing agglomeration and reduce its various positive effects. In addition, the growth of urban fragmentation will promote the accumulation of population and economy in multiple core cities, resulting in an increase in pollution sources and pollution emissions.

Conclusions and Policy Recommendations

This paper takes 283 prefecture-level cities from 2006 to 2016 in China as the research sample. We use the spatial econometric model, panel threshold model, and moderating effect model to study the relationship and mechanism among manufacturing agglomeration, urban form, and haze pollution. The main conclusions and policy recommendations of this study are as follows:

(1) The impact of manufacturing agglomeration on haze pollution shows an inverted U-shaped relationship that promotes first and then inhibits. This indicates that when manufacturing agglomeration is low, further increasing the level of manufacturing agglomeration will only aggravate haze pollution. However, when the level of manufacturing agglomeration reaches a specific threshold, it has a significant inhibiting effect on haze pollution. Therefore, we need to adopt targeted agglomeration policies according to different levels of manufacturing agglomeration. When manufacturing agglomeration is low, the government needs to introduce strict environmental regulation policies to force manufacturing enterprises to improve their technological innovation capabilities. In addition, we should enhance the spatial concentration of the manufacturing industry so that the level of manufacturing agglomeration can reach an ideal stage where it can play a significant emission reduction effect. When the degree of manufacturing

agglomeration exceeds the critical value, the positive externalities of manufacturing agglomeration, such as technology spillover, cost-saving, and facility sharing, gradually become prominent. Thus, the economies of scale of manufacturing agglomeration should be exploited. At the same time, the government should also be wary of the crowding effect that the excessive aggregation of manufacturing industries may bring about. And the negative impact of excessive agglomeration on the economy and the environment can be mitigated through industrial transfer policies.

(2) The haze pollution in Chinese cities presents a significant spatial spillover effect, with haze pollution in one region significantly aggravating haze pollution levels in neighboring cities. Therefore, haze reduction policies should take spatial spillover factors into account. The government should break down the administrative barriers between regions and strengthen the cooperation between regions on haze pollution control to realize the coordinated development of economic development and environmental protection. Fundamentally speaking, to establish a long-term and effective cooperation mechanism for haze pollution control, we must first divide the responsibility for pollution control and further form a unified environmental management standard and policy system through regional negotiation. Secondly, actively build a reduction information sharing network and a unified environmental pollution monitoring platform based on acceptable development ideas and concepts. Therefore, the government can create a strong synergy in the fight against haze pollution by jointly implementing environmental management programs.

(3) The regional empirical results demonstrate that the impact of manufacturing agglomeration on haze pollution in eastern and central China shows an inverted U-shaped curve relationship of first promoting and then inhibiting. However, there is no inverted U-shaped relationship between the impact of manufacturing agglomeration on haze pollution in the western region. On the one hand, the eastern and central areas should use their existing advantages, such as abundant human resources, substantial capital, and excellent infrastructure, to further enhance their independent innovation capabilities. This will promote the high-quality development of the manufacturing industry, thereby alleviating the negative impact of manufacturing agglomeration on the ecological environment. On the other hand, the western region should attract enterprises, capital, and technology-based on its advantages such as abundant resources and low cost of production factors. In this way, the level of manufacturing agglomeration in the region will be improved, and the process of new industrialization will be accelerated. At the same time, strict environmental protection reviews should be set up for newly entered enterprises and technologies to avoid the influx of polluting enterprises.

(4) There is heterogeneity in the moderating effect of changes in the urban form on manufacturing agglomeration and haze pollution. And the external shape complexity of cities strengthens the relationship between the concentration of manufacturing and haze pollution. When the manufacturing agglomeration level is on the right side of the inverted U-shaped curve, the relationship between the two is not moderated by the complexity of the external shape of the city. Urban compactness has no moderating effect on the connection between the two. And urban fragmentation positively moderates the relationship between manufacturing agglomeration and haze pollution. When the level of manufacturing agglomeration crosses the inflection point, urban fragmentation has a negative moderating effect on the connection between the two. Based on this, we must first strengthen infrastructure construction, especially to expand to the city boundary. This can avoid reducing manufacturing agglomeration levels due to the crowding effect on the city

boundary, making it difficult to exert positive effects such as centralized pollution treatment. Secondly, the improvement of urban compactness is conducive to exerting the economies of scale of manufacturing agglomeration. Thus, it is necessary to make full use of factor pooling, knowledge sharing, and technology spillover to promote urban green development. Finally, the government should speed up the flow of factors between cities and strengthen the division of labor in industry and knowledge innovation. In this way, we can enhance the functional relevance and complementarity between each other and gradually form a spatial collaboration network system based on the comparative advantages of each city.

(5) The urban form has a significant double threshold effect on haze pollution. With the increase in the complexity of the external shape of the city, it can effectively suppress the haze pollution, but the influence coefficient gradually weakens. When it crosses the double threshold, the urban exterior shape complexity shows a promoting influence on haze pollution. When urban fragmentation is the threshold variable, the increase in urban compactness is conducive to reducing haze pollution. When urban fragmentation is used as the threshold variable, the effect of increasing urban fragmentation on haze pollution shows the characteristics of first inhibition and then promotion. On the one hand, enhancing the ventilation capacity of cities can effectively alleviate haze pollution. Thus, the government can try to build urban ventilation corridors and adjust the pollution sources to locations with better air circulation. On the other hand, it further exerts the agglomeration effect of compact urban development to promote green technology innovation. Second, consider the simultaneous advancement of land expansion, infrastructure, and greening construction. And focus on the synergy of economic and ecological benefits. Finally, promote the optimal allocation of factors among different cities, and guide the rational accumulation and distribution of industries.

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