



Spatial–temporal heterogeneity and influencing factors of the coupling between industrial agglomeration and regional economic resilience in China

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Abstract

The coordinated development of industrial agglomeration and economic resilience can drive regional economic advantages; this type of development has become a catalyst for sustainable growth and high-quality development of the economy in China. This study applied models, including the coupling coordination degree, spatial autocorrelation, and Tobit, to explore the heterogeneous characteristics of the coupling of China's industrial agglomeration and regional economic resilience from 2005 to 2019. Additionally, by applying the perspectives of economic and geographic location, indicators were selected to analyze the associated influencing factors, including industrial externalities, new economic geographies, economic policy factors, and other aspects. We found that the overall coupling between industrial agglomeration and economic resilience increased over the study period, but with only a moderate level of coordination. Provinces with high, moderate, and low levels of coordination eventually emerged along a strip-like alternating pattern in space. The dependence increased with an increase in space, but was not significant, and there was a lack of benign interaction between the regions. With respect to interactivity between locations, the interaction of the east and the coast was the most active. There were lower levels of interaction between the west and inland regions. This further confirmed the significant temporal and spatial heterogeneity of the coupling. Environmental pollution, market consumption, the quality of space, and technological support significantly promoted the coupling; opening to the outside world did not. Specifically, with respect to economic location, market consumption and spatial quality had a significant positive effect on the eastern coupling. The center and west regions were significantly affected by economic density and market consumption, and the northeast region was affected by spatial quality and capital intensity. Concerning geographical location, market and technological forces strongly promoted interactions in both the coast and inland regions. The study found that both the government and the market need better guidance to effectively engage with and shape industrial agglomeration and economic resilience in a scientific, reasonable, localized, and distinctive manner.

Keywords Industrial agglomeration · Regional economic resilience · Coupling · Influencing factors · China

1 Introduction

In the new era of economic transformation, enhancing regional economic resilience is an important part of economic development, and is a strategic requirement for China to achieve high-quality development. For important industries supporting economic development, promoting integrated development through agglomeration has become an effective and universal approach to achieve industrial growth. Industrial agglomeration further supports the realization of stable and long-term resilient economic development (Yu et al., 2020). Especially under the impact of the COVID-19 epidemic, industrial agglomeration reflects strong competitive advantages and synergies. At the same time, it enhances economic resilience and ensures sustainable, stable, and healthy economic growth (Han, 2020). Therefore, when facing a future uncertain environment, encouraging the coupling and synergy of industrial agglomeration and economic resilience has become an important focus of China's high-quality development strategy (Liu, 2020; Zhao & Wang, 2021). It is also an effective choice for supporting regional integration and sustainable economic development.

Therefore, based on China's industrial economy and the changing external environment, this study asks the following questions. What are the interactive characteristics of industrial agglomeration and regional economic resilience? How can China best synergistically improve the level of "resilience" and "aggregation" in the high-quality transformation of the economy? What are ways to enhance and expand the capability and space of the economy to successfully mitigate an uncertain future? To address these questions, based on coupling coordination degree, spatial autocorrelation, and Tobit model, this study focuses on the regional economy to analyze the spatial-temporal heterogeneity of the coupling between China's industrial agglomeration and regional economic resilience. Furthermore, the study explores the influencing factors involved, and further provides an experiential reference and policy guidance for the benign interaction.

Given this background, this paper makes the following contributions to the field. First, on the theoretical level, the existing literature has not fully addressed the coupling interaction between industrial agglomeration and regional economic resilience. This paper studies the concepts of agglomeration and resilience in the same theoretical framework, further enriching theories related to the agglomeration economy and regional economic resilience. Second, this study takes a realistic approach to investigate the spatial-temporal heterogeneity of the coupling between industrial agglomeration and economic resilience from an economic perspective or geographical location. This deeply analyzes the healthy and sustainable development of the industrial space within the region, which encourages interactions according to local conditions, and plays a positive role in realizing regional integrated development. Third, at the level of influencing factors, this study identifies the influencing mechanisms driving the coupling between industrial agglomeration and economic resilience, which is based on the market, space, environment, and other aspects. This provides a decision-making reference for effectively implementing industrial policies and improving economic resilience, and for promoting the synergy and high-quality development of industry and the economy in China.

In short, this paper offers a perspective for improving the efficiency of industrial agglomeration and building a resilient space carrier that supports economic growth and promotes economic optimization. Simultaneously, the study may also help China balance growth and stability in a "new normal" environment, and provides important policy implications for choosing an appropriate strategic coupling model for industrial agglomeration

and economic resilience. In addition, the main conclusions of this paper provide new solutions for the mid- and long-term recovery of China's economy in the post-epidemic era, as well as the reshaping of a more inclusive and sustainable development path.

2 Literature review

2.1 Research on industrial agglomeration and regional economic resilience

Industrial agglomeration refers to the concentration of different enterprises in the same industry, or related enterprises in different industries, within a geographical unit. Elements such as capital, manpower, and technology then continue to converge and develop within a spatial range. Industrial agglomeration helps shape regional characteristics and competitive advantages, encourages certain economic effects, and is an important engine of regional growth (Chen, 2019). Through resource sharing, scale effect, knowledge spillover, and technological innovation, industrial agglomeration can improve the efficiency of resource allocation, and promote economic transformation and industrial synergy (Lu et al., 2021; Yu et al., 2020). The theory of industrial agglomeration originates from industrial location theory, which emphasizes the geographical proximity of related industries. Agglomeration economic theory, new industrial space theory, new competitive advantage theory, path dependence theory, and new economic geography have laid a rich theoretical foundation (Henry et al., 2021; Hu et al., 2021). As the industrial chain has modernized, the clustering chain has deepened the economic transformation. This has continuously evolved innovation in industrial agglomeration, and the optimization of the scale of industrial agglomeration. Subsequently, the drivers for agglomeration have been analyzed, including natural resources, market capacity, infrastructure, and policies (Fujita & Thisse, 2005; Jie et al., 2020).

With respect to the form of development, as a form of spatial organization within the context of the division of labor, industrial agglomeration is mainly manifested in terms of specialization and diversification. The concept of specialization agglomeration can be traced back to Marshall's industrial location theory. This form of agglomeration emphasizes that knowledge spillovers within the same industry can create a collaborative and innovative environment (Galliano & Magrini, 2015). However, there may also be pollution spillovers (Hao et al., 2021). Diversified agglomeration has also been widely recognized as encouraging technological innovation and structural transformation (Hardy et al., 2018; Yu et al., 2020). To measure this agglomeration, based on different perspectives, scholars have used indicators such as location entropy, the Herfindahl–Hirschman Index (HHI) index, and the spatial Gini coefficient to measure industrial agglomeration (Pei et al., 2021). Some scholars have also measured it using the EG and MS index, and from the perspective of distance (Chen & Wu, 2021; Hu et al., 2021).

Regional economic resilience emphasizes the ability of the regional economy to withstand shocks when addressing external fluctuations, or the ability to successfully transform from an old-growth model and achieve development during a shock (Hu & Yang, 2019; Liu et al., 2020). The existing literature emphasizes the concepts of equilibrium and evolution, and is mostly based on the dimensions of resistance, resilience, relocation, and renewal (He & Chen, 2019; Martin & Gardiner, 2019). Economic resilience is characterized by stable macroeconomics, inclusive infrastructure, and diverse industrial structures (Faggian et al., 2018; Iordan et al., 2015). It is also manifested by striving to break through functional,

cognitive, and political lock-in, and by a continued consolidation of resilience, reorganization, and creativity (Li et al., 2019; Sweeney et al., 2020).

In terms of the research paradigm, there has also been a gradual focus on combining and applying spatial analysis methods based on traditional mathematical characteristics, mainly including the core variable and the index system methods (Eraydin, 2016). Most studies have used data such as output values, employment, and foreign trade to measure regional economic resilience at multiple scales. Case studies have included the European Union, individual countries, and urban and rural area contrasts (Doran & Fingleton, 2016; Li et al., 2020). Political, historical, and cultural factors have also gradually been factored into studies on economic resilience (Cainelli et al., 2017; Hu & Yang, 2019).

For research hotspots, there have been three main specific areas of intensive research. The first has involved coupling research on the multidimensional resilience of economic and social, ecological, or other systems. Resilience has been gradually introduced into the category of spatial economics, with studies discussing the coupling mechanism of resilience between systems under shocks (Folke et al., 2010; Hardy et al., 2018; Zhang et al., 2021). For example, the differentiation and integrity of resilience in the developed Guangdong-Hong Kong-Macao Greater Bay Area and Yangtze River Delta have been a focus of attention (Liu et al., 2020; Zhang & Feng, 2019).

The second intensive research area has applied complex system theory to explore regional economic resilience, integrating such frames as engineering, ecology, adaptability, and resilience. In the face of new unknown risks (such as COVID-19), for which priori probabilities nor clear consequences are available, scholars have also emphasized the need for regions to address invalid “hypotheses.” This has extended resilience research into the areas of “ambiguity” and “uncertainty” (Pendall et al., 2010; Qiu, 2018; Shamsuddin, 2020).

The third intensive research area involves the complex evolutionary mechanism of regional resilience. The trajectories of nonlinear and multiple evolutions of economic resilience and geographic differences have attracted the interest of many scholars. The causal mechanisms involved in the interaction, confrontation, feedback, and mutation between influencing factors and resilience are complex. Such factors include industrial structure, institutional culture, knowledge bases, and psychological cognition (Fahlberg et al., 2020; He & Chen, 2019; Ling, 2021; Liu, 2020).

Therefore, given interference and shock from different uncertain factors, such as politics and climate, scholars have explored how regions can combine their own advantages to build industrial agglomeration with regional characteristics and competitiveness. In addition, scholars have explored paths to actively adapt to the new environment and achieve the synergy between industry and economy (Tan et al., 2020; Wang & Zhong, 2021). This has become an urgent research topic to inform the long-term high-quality development of regional economies.

2.2 The relationship between regional economic resilience and industrial agglomeration

In the context of the interaction between economic globalization and localization, regional economic resilience is reflected in the resilience of industrial clusters. Existing studies have applied theoretical frameworks, such as evolutionary economic geography (Kitsos et al., 2019; Tan et al., 2020), to propose that the structure of regional industrial agglomeration is the most important and direct factor impacting regional economic resilience. An advanced

industrial structure has significant agglomeration characteristics, and agglomeration can maximize the advantages of economies of scale and scope, creating a circular accumulation effect. This, in turn, can help regions mitigate economic crises (Rocchetta & Mina, 2019; Zhang & He, 2020). Specifically, the initial industrial structure provides a basis for an economy to resist external shocks. In addition, the diversified industrial structure has an “automatic stabilizer” function that diversifies risks and resists shocks. As a result, the structural optimization based on diversified industrial agglomeration becomes a driving force for sustained economic resilience (Brown & Greenbaum, 2017; Cainelli et al., 2017; Xu & Deng, 2020). However, excessive dependence may limit regional development and increase the risk of external shocks. For example, Hu and Yang (2019) noted the related diversified export product structure may be reversed, and have a “negative information spillover” effect during periods of declining external demand. This may inhibit the resilience of industrial exports. Therefore, scientific and rational industrial agglomeration is important for fully maximizing and cultivating comparative advantages and building a more economically resilient region.

In addition to explore the impact of industry specialization or diverse agglomeration structures on regional economic resilience, scholars have also used indirect factors to analyze the relationship between agglomeration and resilience, mainly by analyzing knowledge spillovers, technological innovation, and other mediators (Bishop, 2019; Wang & Zhong, 2021; Yu et al., 2020). Industrial agglomeration impacts economic resilience by changing the industrial collaboration, and through sharing, matching, and learning mechanisms that effectively exert entrepreneurial innovation. This can influence innovation and reorganization. The spillover of knowledge and technology between industries may stimulate regional innovation, promote the high-end value chain of industries, and enhance economic resilience (Behrens et al., 2020; Xu & Deng, 2020). Therefore, industrial agglomeration is an important way to realize overall technological progress in an industry. Agglomeration stimulates the generation of technological innovation, enhancing the ability of the relevant industrial system to resist shocks and the ability to move toward a new growth model (Ghouchani et al., 2021; Rocchetta & Mina, 2019). In addition, studies have explored the relationship between industrial agglomeration and economic resilience from other perspectives. For example, Yu et al. (2020) proposed a “technology-relationship-market” model, emphasizing that after a region is affected by external shocks, clusters experience interactive responses in these three dimensions (technological innovation, relational governance, and market diversification) to achieve recovery. Su and Zhao (2022) noted that the scale of the manufacturing industry may improve the economic resilience, by the resource allocations and production advantages of information agglomeration.

The research described above highlights the role of positive externalities in industrial agglomeration; these externalities are an internal driver for improving the resilience of the regional economy. First, externalities can effectively decrease the vulnerability of the regional economic system to disturbances. They can also increase the regional economy’s ability to resist and absorb shocks, improving the sustainability of the regional economy (Chen & Wu, 2021; Lu et al., 2021). Second, it can effectively restore the economic system, reintegrate internal resources, and adjust its own structure; these conditions improve the adaptability of the regional economy (Zhang & Feng, 2019; Zhao & Wang, 2021). Third, knowledge spillovers and other factors help the regional economy open a new growth path after a shock, enabling it to return to stable growth. This improves the variability of the regional economic system (Kitsos et al., 2019). Improvements in the sustainability, adaptability, and changeability of the economic system also promote improvements in regional opening and innovation, achieving the stable, sustainable, and high-quality growth

of the economy (Rocchetta & Mina, 2019). Consequently, industrial agglomeration creates advantages with respect to high productivity and high-end resource agglomeration. This, in turn, leads to a stronger industrial chain and enhances economic resilience (Liu et al., 2020; Wang & Zhong, 2021).

Therefore, promoting industrial agglomeration has become an important path for enhancing regional economic resilience. The enhanced resilience creates a stable and favorable industrial environment for industrial agglomeration (Behrens et al., 2020; Sun et al., 2022). With the continuous release of the scale and market effect of industrial agglomeration, regional economic benefits and synergies have improved, and economic resilience has been enhanced. Regions need to promote the formation of effective agglomeration and industrial integration, eventually creating a virtuous circle of industrial agglomeration and economic resilience (Boschma, 2015; Zhang & He, 2020).

2.3 Literature summary

In summary, the main studies about industrial agglomeration and regional economic resilience have revealed the following. First, theoretical and empirical studies on industrial agglomeration and regional economic resilience are relatively mature, and have mainly focused on the impact of short-term crises on industries and the economy. However, empirical studies exploring the long-term interaction between the two are lacking, especially with respect to the temporal and spatial evolutionary characteristics. Given the new development pattern of China, more studies are needed that involve empirical research on their synchronous interactions, revealing systematic laws governing the heterogeneity of spatial–temporal evolution. Second, some studies have focused on the relationship between industrial agglomeration and regional economic resilience. With respect to industrial agglomeration, research has focused on analyzing the impact of industrial agglomeration on economic resilience through positive externalities, such as knowledge and technology spillovers. However, few studies have integrated the synergistic interaction between industrial agglomeration and regional economic resilience, and comprehensive and systematic quantitative investigations of the characteristics of the interaction are needed. Concerning the location factor, few studies have comprehensively analyzed the interaction from the perspective of economic and geographic location. Third, with respect to analyzing the mechanism of the coupling between industrial agglomeration and regional economic resilience, most studies have focused on the industrial connection and technological innovation within a region. This approach has not fully considered the perspectives of market consumption, environmental pollution, and comparative advantage, and has not addressed the deep-level mechanisms impacting the synergy. In addition, few studies have explored the heterogeneity of influencing factors under different economic or geographic locations.

Therefore, based on the perspectives of economic and geographic location, this study explores the heterogeneity of the spatial–temporal evolution with respect to the coupling between industrial agglomeration and regional economic resilience in China from 2005 to 2019. In addition, this study comprehensively considers the comparative advantage strategy, industrial externalities, and the theory of new economic geography, and analyzes the factors affecting the coupling from environmental pollution, opening to the outside world, market consumption, spatial quality, technological innovation, and other aspects. Therefore, focusing on regional economic research, this study attempts to provide insights and guidance for the synergistic and efficient development of industrial agglomeration and regional economic resilience.

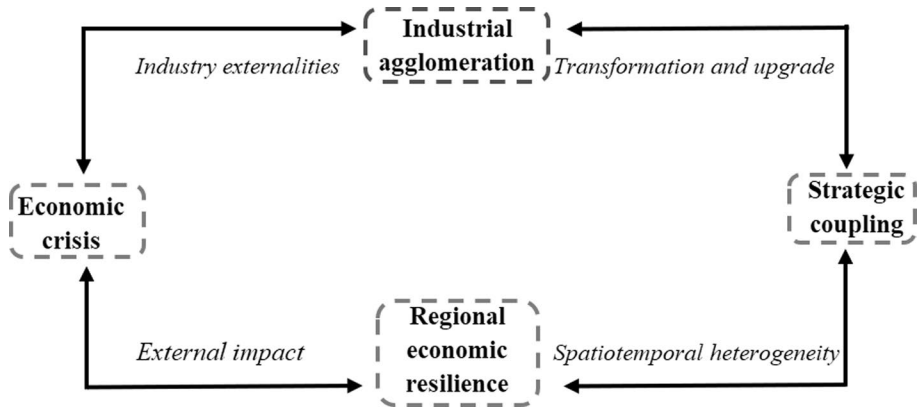


Fig. 1 Mechanism involved in the coupling between industrial agglomeration and regional economic resilience

The rest of this paper is structured as follows. Section 3 analyzes the mechanisms involved in industrial agglomeration and economic resilience, and presents the study methodology. Section 4 presents the results. Section 5 analyzes the influencing factors. Section 6 discusses the results. Section 7 clarifies the conclusions and recommendations.

3 Mechanism analysis and methodology

3.1 Coupling mechanism

Industrial clusters appear hand-in-hand with regional economic development. Regional economic resilience is defined as a region's ability to transform and upgrade industries. The interaction between the two is heterogeneous, because of their different development levels. Industrial externalities and shocks increase the degree of heterogeneity. This highlights the need to explore the strategic integration of economic resilience and industrial clusters, to enhance the stability and sustainability of regional development. Figure 1 outlines the mechanisms described in this section.

Industrial agglomeration has an impact on regional economic resilience. First, industrial clusters produce regional economic effects, mainly due to the economies of scale and scope produced by industrial agglomeration. The theory of an agglomeration economy posits that industrial agglomeration is mainly used for regional economic development through matching, sharing, learning, and other mechanisms. This affects a region's resistance and resilience. Second, industrial agglomeration is associated with certain externalities. Different types of agglomeration have different risk-sharing capabilities due to their inherent structural differences. This results in differences in the resilience of regions in resisting external shocks. Third, industrial agglomeration effectively increases the vulnerability of the economic system to internal and external shocks, and decreases the ability to resist and absorb shocks. It is an important factor affecting regional economic growth and can improve the sustainability, adaptability, and variability of the economy (Fan & Scott, 2003; Liang, 2014).

Regional economic resilience has an impact on industrial agglomeration. First, for innovative industries, economic resilience ensures that the entire industrial cluster advances in a stable and upward direction, supporting the stability of industrial clusters. Second, for resource industries, applying economic resilience theory can ensure the correct use of resources, and build an effective balance between resource consumption and economic development, based on a reasonable consideration of other factors, such as environmental protection, human, and historical factors. Third, for emerging industry clusters, regional economic resilience can ensure overall stable development, and minimizes transformational plasticity and the possibility of fracture.

Therefore, in actual development, industrial clusters with economic resilience can promptly eliminate incorrect asset allocation policies, pursue sufficient stability, and maximize market flexibility. This can promote high-quality economic development while ensuring economic stability (Chen, 2019).

3.2 Data sources

This research focuses on China's provincial administrative region as the research unit. A total of 31 provincial administrative regions were included in the study. They are collectively referred to as "provinces" (including municipalities and autonomous regions). The research period was from 2005 to 2019, and the data used were mainly collected from the "China Industrial Economic Statistical Yearbook," "China City Statistical Yearbook," "China Statistical Yearbook," "China Price Statistical Yearbook," statistical yearbooks of each province, and other resources. The statistical caliber of the data for industrial sub-sectors has changed significantly since 2004, so specific data for some industrial sub-sectors were obtained from the "China Economic Census Yearbook." These data included industrial pollutant emissions; other data were derived for multiple years from the "China Environmental Statistical Yearbook." The relevant data for 2016–2019 were based on data totals for specific cities in the "China City Statistical Yearbook." The remaining missing data were adjusted using the imputation method. Due to data limitations, the study does not include Taiwan, Hong Kong, and Macau.

4 Research methods

(1) Regional economic resilience

This study draws on the regional economic resilience measurement method introduced by Martin et al. (2016), which is generally accepted as a consensus approach. This method tests the relative resilience of each study area in response to a shock when it occurs, and measures the differentiation of the economic operation of each study area when the shock does not occur during normal times. The formula is:

$$\text{Resis}_i^t = (\Delta Y_i - \Delta E) / |\Delta E| \tag{1}$$

In this formula, Resis_i^t is the relative economic resilience of the i object in year t . In this context, the object is the province. The parameter ΔY_i is the actual economic operation status of the i object, as expressed in formula (2); and ΔE is the predicted economic operation status of the object. This is based on the overall economic operation status of the region where the object is located, specifically from formula (3).

$$\Delta Y_i = Y_i^t - Y_i^{t-k} \tag{2}$$

$$\Delta E = ((Y_r^t - Y_r^{t-k}) / Y_r^{t-k}) Y_i^{t-k} \tag{3}$$

In the formula, Y_i^t and Y_i^{t-k} are the quantitative indicators of the study area i at time t , $t - k$. The parameters Y_r^t and Y_r^{t-k} are the quantitative indicators of the reference area where the research object is located at time t , $t - k$. In this study, an example of quantitative indicators is the gross domestic product (GDP).

To facilitate calculations (Liu et al., 2020), formula (1), formula (2), and formula (3) are combined and simplified as:

$$\text{Resis}_i^t = \frac{(Y_i^t - Y_i^{t-k}) Y_i^{t-k} - (Y_r^t - Y_r^{t-k}) / Y_r^{t-k}}{(Y_r^t - Y_r^{t-k}) / Y_r^{t-k}} \tag{4}$$

Based on previous research, GDP indicators reflect economic resilience. Finally, when a shock occurs, the resilience of each province is calculated, allowing the shocks to be compared.

(2) Industrial agglomeration

Industrial agglomeration usually refers to the intensity of production activities in a certain industrial sub-industry in a unit of space. The current mainstream measurement indicators mainly include the Herfindahl–Hirschman Index (HHI), Economic Density Index, Location Entropy, Space Gini Coefficient, and Industrial Concentration. Of these, HHI measures the degree of industrial agglomeration, and is used by government departments and economists. This indicator has the advantages of both relative and absolute concentrations. It is not affected by the number and scale of enterprises, and effectively measures the level of regional industrial agglomeration. Given the availability and feasibility of the sample data, this study applied HHI to measure the level of industrial agglomeration in the reference area of China. Using the method adopted by Fan and Scott (2003), the calculation is as follows:

$$\text{HHI} = \sum_{j=1}^{27} \left(\frac{l_{ij}}{l_j} \right)^2, \quad l_j = \sum_{i=1}^{31} l_{ij} \tag{5}$$

In this formula, $i = 1, 2, \dots, 31$ represent the different provinces, and $j = 1, 2, \dots, 27$ represent industrial subdivisions.¹ The parameter l_{ij} is the number of employees in the j industry of province i ; and l_j is the number of employees in j industry in China overall. A HHI value of 1 indicates that all industries are concentrated in the same area for development. A HHI value of 0 indicates that industries are evenly distributed in different areas.

(3) Coupling coordination degree

Coupling determines the trend of the system in moving from disorder to order. The coupling model is an effective measure of the degree of mutual influence and interaction between systems. The coupling model based on the coefficient of variation is usually used to analyze the coupling relationship between systems. That is, the degree of coupling coordination is calculated to represent the coupling status; this is denoted as D (Lu et al., 2017). To facilitate horizontal comparison, a D value between 0 and 0.3 indicates low coordination, that is, the effective interaction between systems is weak, and there may be mutual consumption. A D value between 0.3 and 0.5 indicates moderate coordination; the level of coupling among systems is insufficient, but there is a trend toward optimization. A D value between 0.5 and 1 indicates a high degree of coordination, with a strong degree of benign coupling and coordinated development.

(4) Global autocorrelation

Global autocorrelation is used to reflect the overall trend of the spatial correlation of the observed variables across an entire study area. This study applied ArcGIS and GeoDa software to calculate the global autocorrelation of the coupling coordination degree of China's industrial agglomeration and economic resilience from 2005 to 2019. Global Moran's I index was used to analyze the spatial correlation; details are in Luo et al. (2015).

(5) Comprehensive environmental damage index model (CEDI)

An environmental damage index indicates the degree of environmental damage caused by a certain type of industrial waste to a region. However, the index does not explain the comprehensive environmental damage caused by multiple pollutants in a region. Given this, this research applies the processing method of Pei et al. (2021). Based on the obtained environmental damage indexes of industrial sulfur dioxide, industrial sewage, and industrial smoke and dust, this study applied the entropy method to determine the weight of the environmental pollution of the three industrial wastes. More specifically, the CEDI was used to measure the degree of industrial pollution in each region.

There is no specific unit associated with the environmental damage index for the three types of industrial wastes; as such, we did not need to standardize the data for this study. The proportion of pollutant k in province i is calculated as:

¹ Based on the availability of data from the "Statistical Yearbook of China's Industrial Economics," this study selected 27 double-digit industries for research. Specifically, from 2005 to 2011, the industry was selected according to the national economic industry classification standard (GB/T4754-2002); from 2012 to 2019, the industry was selected according to the national economic industry classification and code (GB/T4754-2011). Due to the differences in the statistics associated with the two industry classification standards, when calculating the industrial agglomeration, automobile manufacturing and the railway, shipbuilding, aerospace and other transportation equipment manufacturing were combined into the transportation equipment manufacturing industry for 2012–2019.

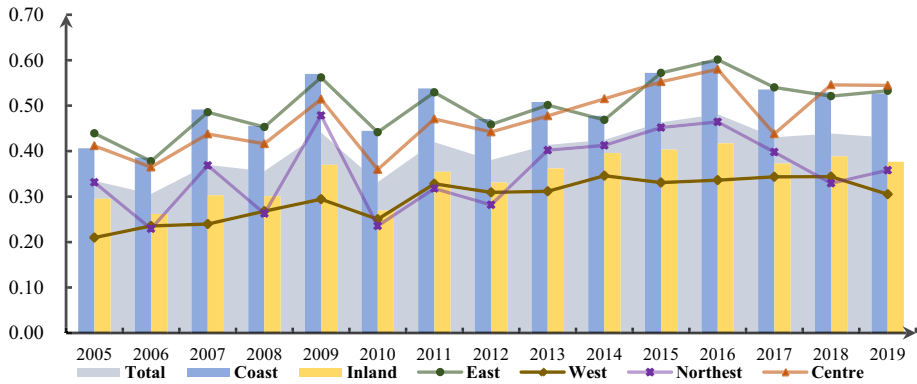


Fig. 2 Coupling coordination degree of industrial agglomeration and regional economic resilience

$$f_{ik} = \frac{EDI_{ik}}{\sum_{i=1}^{31} EDI_{ik}} \tag{6}$$

The information entropy of the k pollutant is further expressed as:

$$e_k = - \frac{1}{\ln n} \sum_{i=1}^{31} (f_{ik} \times \ln f_{ik}) \tag{7}$$

Using the information entropy of each pollutant, the weight of pollutant k is further calculated as:

$$g_j = \frac{(1 - e_j)}{\sum_{i=1}^3 1 - e_j} \tag{8}$$

Combining the weight of pollutant k and the relative environmental damage index, we further calculate the comprehensive environmental damage index:

$$CEDI = \sum_{k=1}^3 f_{ik} EDI_{ik} \tag{9}$$

A higher CEDI index value is associated with a higher level of environmental pollution in the region. In contrast, a smaller index is associated with a lower pollution level.

5 Coupled spatial-temporal heterogeneity

5.1 Characteristics of temporal heterogeneity

From 2005 to 2019, the overall coupling of China’s industrial agglomeration and economic resilience was at a moderately coordinated level; however, there was a trend toward increased volatility (Fig. 2). Most provinces with low coordination evolved to be highly coordinated provinces with an advantage in synergistic growth. Of the provincial administrative units, 48.39% had a degree of coupling coordination that was higher than average.

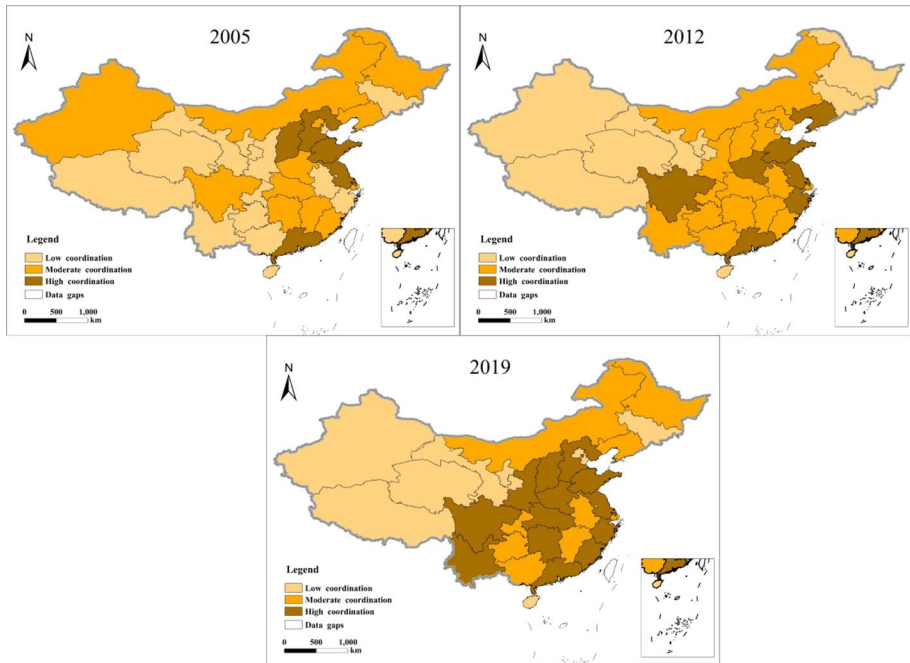


Fig. 3 Spatial distribution of the coupling

Of these, Guangdong had a prominent advantage, whereas Tibet and Ningxia did not. This indicates that the interaction effect was not fully realized. The absolute difference in the coupling increased, reaching 0.91 in 2019. However, the relative difference was comparatively stable at 0.51, especially in Xinjiang and Heilongjiang.

In terms of economic location, the coupling evolved from a pattern where the coupling was higher in the east region compared to the central, northeast, and west regions (in descending order) to a pattern where the coupling was higher in the central region compared to the east, northeast, and west regions (in descending order). Specifically, the interaction between the east, central, and west regions took the shape of a stair-climbing trend. The increase from 2012 to 2019 was particularly significant, especially in the central region, which increased by 31.71 percentage points. This was closely related to the transfer and acceptance of industries and the growth of industrial parks.

The northeast has an old industrial base, with a large range of fluctuation with respect to the coupling. It lacks the efficient integration of industrial clusters, leading to a gradual decline in industrial cluster. This highlights the urgency of eliminating the original path dependence, exploring a new cluster development in the industry, and creating a competitive advantage. This strategic choice could promote industrial development and revitalize the northeast. The diversified agglomeration in the east quickly absorbs, dissolves, and transfers the negative effects caused by external shocks. With respect to geographic location, coupling was consistently higher for coastal provinces compared to the inland. The interaction on the coast was more active than the inland; however, the fluctuation trends were roughly consistent during the study period, with a gentle upward trend. This shows that the interaction between industrial agglomeration and regional economic resilience reflects a certain degree of heterogeneity over time.

Table 1 Moran's *I* index of the coupling

Years	K-nearest neighbor			Distance zone		
	Moran's <i>I</i>	<i>P</i>	<i>Z</i>	Moran's <i>I</i>	<i>P</i>	<i>Z</i>
2005	0.168	0.036	1.972	0.128	0.036	1.967
2006	0.027	0.273	0.578	-0.016	0.374	0.236
2007	0.114	0.088	1.389	0.165	0.025	2.388
2008	0.048	0.214	0.766	0.037	0.188	0.827
2009	0.169	0.041	1.912	0.202	0.014	2.842
2010	0.072	0.169	0.994	0.029	0.223	0.730
2011	0.059	0.190	0.870	0.030	0.211	0.734
2012	0.098	0.116	1.198	0.097	0.077	1.541
2013	0.150	0.050	1.711	0.171	0.019	2.505
2014	0.104	0.105	1.296	0.017	0.238	0.639
2015	0.186	0.032	2.055	0.189	0.019	2.691
2016	0.157	0.043	1.817	0.075	0.100	1.316
2017	0.116	0.083	1.419	0.036	0.195	0.810
2018	0.136	0.061	1.627	0.037	0.185	0.853
2019	0.184	0.030	2.000	0.181	0.020	2.595

5.2 Characteristics of spatial heterogeneity

Figure 3 shows a spatial imbalance in the degree of coupling coordination between industrial agglomeration and economic resilience from 2005 to 2019 in China. In 2005, the coupling coordination of China's industrial agglomeration and economic resilience was intricately distributed overall. Specifically, the low coordination class showed a scattered pattern, mainly concentrated in the central and west regions. There was an uneven distribution of the moderate coordinated class; the distribution took the form of a ring-shaped cluster at the border and in central regions, such as Sichuan and Hunan. The highly coordinated class was relatively sparsely distributed, and was mainly concentrated on the coast.

In 2012, the coupling showed an overall block-like distribution. Specifically, the low coordination class was polarized in the east and west ends of China, decreasing from 14 provinces to 8. The moderate coordination class was distributed in an hourglass shape that was compact in space, reflecting agglomeration characteristics. The highly coordinated class increasingly showed a fragmented distribution of star points; however, the coast still accounted for the majority.

In 2019, the coupling showed an alternating distribution in the shape of overall strips. Concretely, the low coordination class was concentrated in the northwest of China, with a centralized distribution trend. The medium coordination class was distributed in a band with a reduced area, concentrated in the central and northeast regions. The highly coordinated class was mainly distributed along the traffic axis, horizontally along the Longhai line; and longitudinally along the Baocheng-Chengkun line, Beijing-Guangzhou line, and the coastal line. The number surged and was concentrated in the southeast of China. This further shows that the coupling was spatially heterogeneous.

Table 1 shows the comparative results when setting K-nearest neighbors and distance bands, based on the spatial distance weight. *Global Moran's I* was used to determine whether there was autocorrelation in the space, with a range of $[-1,1]$. A range of $(0,1]$ indicates a positive correlation between geographic entities. A range of $[-1,0)$ indicates

a negative correlation. A value of 0 indicates no correlation. Combining the results indicated that the range of *Global Moran's I* was $[-0.016, 0.202]$. Through the P value and Z value, it is found that although there are a few years that are not significant, the research period as a whole passes the test. Furthermore, the fluctuation in the *Global Moran's I* indicated that the degree of the coupling coordination of China's industrial agglomeration and economic resilience generally increased during the study period. That is, there were specific characteristics associated with spatial agglomeration, and the spatial dependence showed a trend of increasing fluctuations. The results of the K-nearest neighbor method indicate that the increases in volatility gradually became smaller. The distance-weighted results indicate that the value in the final period was higher than the initial period; however, the volatility was not stable. This further shows that the spatial agglomeration of the coupling between industrial agglomeration and economic resilience was not particularly significant. This type of benign interaction has not formed a spatial contagion and linkage effect. Furthermore, the active interaction was weak, further confirming the presence of spatial heterogeneity.

6 Analysis of influencing factors

6.1 Index selection

Past research in comparative advantage strategy, industrial externalities, new economic geography, and economic policy was used to identify the factors most likely to influence the degree of coupling coordination between China's industrial agglomeration and economic resilience in 2005–2019. Drawing on relevant research (Chen & Wu, 2021; Ghouchani et al., 2021; Xu & Deng, 2020), we scientifically selected some factors. These factors included environmental pollution, openness to the outside world, market consumption, spatial quality, economic density, capital intensity, and technological expenditures. Specifically, environmental pollution (Hsh) was represented by CEDI model. The degree of openness was represented by the nominal proportion of foreign domestic investment (Fdi). Market consumption (Mar) was expressed as the proportion of total retail sales of consumer goods in the country. Spatial quality (Tra) was represented by per capita highway mileage. Economic density (Den) was expressed by the GDP of the researched province in the area of the administrative units. Capital intensity (Cin) was expressed by the ratio of the actual total fixed assets of the industrial sector to the annual average number of employees. Technological support (Tec) was expressed in terms of technology spending. Production efficiency (Pro) was expressed by the labor productivity of each region.

6.2 Model building

Considering the variables associated with the influencing factors and the Tobit regression model, the relationship equation between the coupling of industrial agglomeration and regional economic resilience and its influencing factors is expressed as:

$$\begin{aligned} OH_{it} = & \beta_0 + \beta_1 \ln Hsh_{it} + \beta_2 Fdi_{it} + \beta_3 Mar_{it} + \beta_4 Tra_{it} + \beta_5 \ln Den_{it} \\ & + \beta_6 \ln Cin_{it} + \beta_7 \ln Tec_{it} + \beta_8 \ln Pro_{it} + \epsilon_{it} \end{aligned}$$

Table 2 Regression results of the factors influencing the coupling between industrial agglomeration and regional economic resilience in China

Explanatory variable	Total	Regional division				Coastal or not	
		East	West	Centre	Northeast	Coast	Inland
Hsh	0.055***	0.092***	-0.070***	0.010	-0.241*	0.064***	0.046**
Fdi	-0.125***	-0.089***	-0.059*	0.081	-0.127	-0.085***	-0.275***
Mar	5.482***	5.332***	4.268***	4.114***	7.934*	5.224***	5.711***
Tra	15.914***	43.677**	-22.413***	38.268	-115.090***	20.004	4.441
Den	-0.021	-0.043*	0.048***	0.126**	0.253*	-0.038*	-0.011
Cin	-0.026	-0.183***	-0.006	0.102	0.268**	-0.110***	0.019
Tec	0.042***	0.049***	0.014	0.040*	0.012	0.049***	0.029***
Pro	0.006	0.175***	0.098	-0.431***	-0.338*	0.077*	0.014

“*, **, ***” indicate the statistical significance level of 10%, 5% and 1% respectively

In this formula, OH_{it} represents the coupling coordination degree of the i region in year t ; $\beta_0, \beta_1, \dots, \beta_8$ are unknown correlation coefficients; and ϵ_{it} are random errors. Some of the explanatory variables were processed in logarithmic form to concentrate the data. Using the Hausman test, if the P value (0.0001) was less than 0.1, there was evidence to reject the hypothesis that there was a random effect and the fixed effects model was adopted. The study used panel data; as such, the fixed panel Tobit model was adopted. The spatial panel Tobit model effectively considers the spatial effect and truncation distribution, yielding more reliable results. This model is significantly better than other models, such as the generalized method of moments. The final results are shown in Table 2.

6.3 Regression results

This study analyzed the effects of different influencing factors on the coupling between industrial agglomeration and economic resilience in China from 2005 to 2019. The results were as follows.

Environmental pollution. The overall regression coefficient of environmental pollution on overall coupling between industrial agglomeration and economic resilience was positive (0.055), indicating a significant positive correlation at the 1% statistical significance level. This shows that environmental damage stimulated the interaction between agglomeration and resilience. Environmental destruction promoted the intensive development of clean technology and other industrial chains, elevating ecological resilience and gradually improved economic resilience. With respect to economic location, an increase in environmental pollution had a positive effect on coupling in the east. A more serious pollution level was associated with a higher interaction. As a traditional old industrial base, the long-term environmental pollution in the northeast is expected to have a negative impact on industrial agglomeration and regional resilience. With respect to geographical location, its impact on coupling was significant, especially for the coast. This is mainly because its industries are developed, and the negative externality of environmental pollution was a dispersive force inhibiting industrial agglomeration.

Openness to the outside world. The overall regression coefficient of openness to the outside world on coupling between industrial agglomeration and economic resilience was

negative (-0.125). This shows that the synergistic interaction was somewhat restrained, and the positive spillover effect should be strengthened. The inflow of foreign investment generally introduces more advanced technologies and a broader international market. However, it can also generate an industrial monopoly, mostly concentrated in labor-intensive industries. Some high-polluting industries have sequentially entered a specific area, resulting in unstable economic growth. Moreover, some industries have relatively high barriers to foreign investment, and domestic industries have not integrated internationally in an orderly manner, weakening the interaction. With respect to economic location, openness had a significant impact in the east and west. This was particularly the case for the east, where the agglomeration of a large amount of foreign investment led to significant interaction. With respect to geographical location, all regions experienced a significant negative correlation at the 1% statistical significance level. Key problems, such as insufficient internal stability while being open, did not support effective interactions.

Market consumption. The overall regression coefficient of market consumption on coupling was positive (5.482), indicating a significant positive correlation at the 1% statistical significance level. This strongly confirms that market consumption generated economies of scale, with a positive effect on the synergy between industrial agglomeration and regional economic resilience. This is because the Chinese market continued to have high development potential, and the active and diversified consumer market attracted the gathering of many industries and companies. This encouraged high-quality industrial development and enhanced economic resilience. With respect to economic location, market consumption of four major economic locations all had a significant positive effect on the interaction, especially in the economically developed east. With respect to geographical location, the positive effect was also extremely strong, especially in the vast inland area. This also encouraged the coordinated development of agglomeration and resilience by increasing market consumption power.

Spatial quality. Spatial quality had a significantly positive effect on overall coupling, with the coefficient reaching 15.914, at a 1% statistical significance level. This shows that improvements in space quality effectively promoted interactions. The cost of space affects industrial agglomeration; as such, improving transportation conditions creates a higher industrial concentration effect. With respect to economic location, the spatial quality had a significant promotion effect on interaction in the east; there was an opposite outcome for the west and northeast. This is mainly because infrastructure construction, manifested as agglomeration in space in the west, is relatively underdeveloped. This expands the spatial difference of coupling and inhibits the coupling. Improving the quality of space does not improve short-term economic resilience. Given the lack of an impact from the short-term effect of space quality, path dependence of the northeast region led to a lack of economic resilience, hindering coupling. With respect to geographical location, the spatial quality did not have a significant effect on the coast or inland.

Economic density. The overall effect of economic density on coupling was not significant. With respect to economic location, the interactive effect of economic density on the coupling positively advanced in the west, central, and northeast regions; this was particularly the case in the west. However, in the east, the influence curve was “displaced,” and did not reach the optimal range to promote coupling. The developed east may have experienced naturally expected contradictions between industry and economy, as there were significant pressures related to industrial transformation and upgrading. Many basic industries gradually shifted, inhibiting simultaneous improvement. The relatively underdeveloped central and west regions actively initiated new industries, gradually increasing their economic density. This promoted industrial agglomeration and strengthened economic resilience. The

geographic location had a restraining effect on the simultaneous development along the coast. Coastal provinces adjusted their industrial structure earlier, and enhanced their resilience, by gradually relying on strategic emerging industries and service industries, instead of their original industries.

Capital intensity. The overall effect of capital intensity on coupling was not significant. With respect to economic location, the capital intensity of the east restrained the interaction. This may be because, while the industries are rich in fixed assets, there are also many employees. However, for the east, where traditional industries have gradually shifted and are actively developing advanced industries, employment pressure has hindered improvements in economic resilience. The northeast experienced a positive effect as it went through a transitional bottleneck period, where capital intensity needed to increase to improve economic resilience. With respect to geographic location, coastal provinces experienced a significant reverse effect. These areas are rich in capital and are densely populated. A larger number of employees is generally associated with a lower capital intensity. In this case, this encourages the stability and sustainability of economic development.

Technological support. The overall regression coefficient assessing the relationship of China's technology on coupling was positive (0.042). This was a significant positive correlation. Among the determinants of industrial agglomeration, technology spillover is an important foundation for industrial innovation and is key to enhancing the ability to achieve economic resilience. With respect to economic location, technology had a significant effect on the east and central regions, especially the east. With respect to total expenditure intensity, and per capita expenditure, the east had an absolute advantage. The east effectively promoted the coordination of multiple industries, and improved the degree of urban diversified production. In recent years, technology expenditures have been redirected toward central regions, significantly supporting industrial agglomeration and strengthening economic resilience. With respect to geographic location, there was a significant positive effect for all regions. This was particularly true for the coastal provinces, where there have been large investments, guiding advanced industrial clusters and further improving economic resilience.

Production efficiency. The overall effect of China's production efficiency on coupling was not significant. In terms of economic location, production efficiency had a significant positive interaction effect on the east region, but had a restraining effect on the west and northeast regions. High-productivity enterprises and highly skilled labor gathered in the east. The east generally relied on technology to improve efficiency, and to advance industrial agglomeration and regional economic resilience in both directions. However, a lag occurred in the west and northeast. With respect to geographical location, production efficiency had a positive effect on coastal provinces. This was due to its comparatively advanced industries and outstanding production efficiency. This positively impacted the synergy between industrial agglomeration and regional economic resilience.

7 Discussion

The impact of the COVID-19 epidemic has highlighted an urgent need for the coordinated development of industrial agglomeration and economic resilience. Previous studies have not provided significant references to inform China's regional integration synergy and high-quality development from the coupling perspective. Therefore, this paper analyzed the heterogeneous characteristics of the coupling between the two from 2005 to 2019, and

analyzed the drivers from environmental, technology, and market perspectives. We applied a popular, accepted, and scientific model to measure industrial agglomeration and regional economic resilience (Fan & Scott, 2003; Martin & Gardiner, 2019). Additionally, combined with existing research (Guo, 2020; Wang et al., 2021; Yu et al., 2020; Zhu et al., 2021), the study analyzed a range of different factors, including market consumption, quality of space, technological support, environmental pollution, and production efficiency. These factors impact both industrial agglomeration and economic resilience, and can also act indirectly through these factors.

First, the result of the temporal heterogeneity analysis found that although the coupling between industrial agglomeration and regional economic resilience rose over the study period, it fluctuated and lacked high interaction. This was consistent with inferences from existing research. Many papers have confirmed the characteristics of industrial agglomeration and the long-term resilience of economic growth in China (Han, 2020; Liu et al., 2020; Wang & Gao, 2020). Further, Zhao and Wang (2021) and Guo (2020) found that industrial agglomeration usually makes the region more resilient. Sun et al. (2022) concluded that the development of both has stage-based volatility, which aligns with our conclusions. The coupling is currently at a moderate level of coordination. This is consistent with Zhang et al. (2021) noted that uneconomical agglomeration created by vicious competition for common development resources among different industries is a problem, and it is necessary to promote a virtuous circle of the two.

From the perspective of economic and geographical locations, each location developed differently. This finding aligns with previous research. Specifically, Liu et al. (2020) applied a strategic coupling model to explain regional differences in economic resilience based on relational economic geography. Liu and Zhang (2021) explored the heterogeneity of the impact of manufacturing agglomeration on resilience, and confirmed that regional differences resulted in agglomeration having different degrees of effect on resilience. The absolute difference became increasingly significant. Zhao and Chen also confirmed differences in the impact of diversification agglomeration on the economic resilience of different locations. They found the largest positive effect in the eastern, coastal, and central regions; the effect in those regions was much higher compared to the west (Chen & Wu, 2021; Zhao & Wang, 2021). This is because the advantages of the coastal and eastern regions, such as the policy system and economic foundation, have attracted significant talent, capital, technology, and other elements. These have had a significant spillover effect on industrial diversification and agglomeration and economic resilience.

With respect to the interactive disadvantage of the west, Guo (2020) found that it has a weak industrial base; the production links between industries are relatively limited; and the relationship between industry-related diversity and resilience has an “inverted U-shaped” relationship. Zhang et al. (2021) also identified that wasted resources, a “congestion effect,” and chain effects are problems in the west. This does not support economic resilience. Additionally, we found that the center region developed later. This reflects the fact that the region already had a foundation for aggregation to accept industries. The synergy between agglomeration and resilience deepened, consistent with the “Rise of Central China” strategy.

Second, according to the spatial heterogeneity analysis presented above, the coupling of China’s industrial agglomeration and economic resilience showed spatial imbalance. Few studies have explored this topic. However, from the standpoint of industrial agglomeration or economic resilience, the two have not been effectively integrated in space. A general consensus has emerged that there is a spatial imbalance in China’s economic development. This has been caused by differences in regional innovation, opening up, and systems;

uneven industrial agglomeration and development (Liu & Zhang, 2021; Yu et al., 2020); and uneven economic resilience (Li et al., 2019; Su & Zhao, 2022). This has eventually led to a lack of equilibrium in the coupling between the two at different locations. Bai et al. (2019) emphasized the diversification in the spatial pattern of resilient systems. Most regions with good economic foundations have strong economic resilience and significant spatial heterogeneity. All of these reflect the spatial heterogeneity of the coupling. Hu et al. (2021) also noted that different regions have different risk-sharing capabilities due to different agglomeration patterns. This, in turn, forms regional differences in resilience against external shocks, which are spatially dispersed.

In addition, due to the influence of administrative region economies and the cross-regional transfer of industries, there is a weak spatial linkage in the coupling. Sun et al. (2022) concluded that local “regulatory leakage” and the “demonstration effect” of a locality may influence the development of industrial agglomeration and economic resilience. This explains why we concluded that the coupling is strip-shaped, rather than point-shaped in space. This also provides a reference for promoting the benign interaction between the two. Simultaneously, this study concludes that provinces with highly coordinated interactions have a spatial advantage. This is consistent with the positive trend of China’s economic development (Han, 2020). Areas with strong interactions became concentrated along the transportation axis and in the southeast. Consistent with the analysis of the development of each location, this is consistent with China’s economic pattern.

Third, to analyze the influencing factors, we reveal the factors that affect the coupling of resilience, including technology, environment, and space. These results align with evidence from similar studies. Wang and Gao (2020) affirmed the positive roles of production efficiency, technological innovation, and market consumption in promoting industrial development and improving economic resilience under the impact of the epidemic, especially technological innovation. Zhu et al. (2021) and Guo (2020) focused on enhancing the resilience of industrial clusters through financial capital, industrial ecology, and transportation facilities. Zhang (2020) emphasized the positive effect of good spatial quality. All these factors provide a healthy competitive environment for clusters, enhancing economic resilience.

However, Guo (2020) and Zhang et al. (2021) also found that the opening up of clusters has a generally negative effect on economic resilience. This is because the more a regional industry depends on foreign investment, the closer the external connection becomes, the easier it is to form path dependence, and the more serious economic fluctuations may become under the influence of external uncertain factors (He & Chen, 2019). This explains the inhibited interaction between the two. Additionally, we conclude that environmental pollution has a positive impact on the interaction between the two. This also shows that the development of agglomeration and resilience has been at the expense of the environment. This highlights the need to seek a scientific development model and strengthen pollution oversight (Hao et al., 2021). Furthermore, our conclusions show that the coupling of production efficiency and capital intensity is not significant. This indicates that the functions of these factors have not been fully maximized and could be improved.

Specifically, the east and coast have clear advantages in market consumption, technological innovation, and production efficiency (Bai et al., 2019). As such, the positive effect on coupling was more significant than other locations. At the same time, those regions are more susceptible to economic fluctuations in peripheral and neighboring cities due to a higher degree of openness (Guo, 2020). Zhao and Wang (2021) emphasized that these areas should continue to optimize space and play a positive role in improving the quality of space. Zhang (2020) noted that spatial quality has a positive effect on the economic resilience of Northeast China, which differs from this study’s conclusions. For many reasons,

our proxy variables vary, and our data have been updated to 2019. In addition, he emphasized that spatial quality can improve economic resilience, and does not involve industrial agglomeration. Spatial quality does not necessarily promote efficient industrial agglomeration, making the coupling effect on the two not as prominent.

8 Conclusions and recommendations

8.1 Conclusions

Using models such as CEDI and Tobit, this study explores the heterogeneity of the coupling between industrial agglomeration and economic resilience in China from 2005 to 2019, and analyzes the influencing factors. The conclusions are as follows.

First, in the face of an external complex environment, the coupling between China's industrial agglomeration and regional economic resilience showed an increase in volatility from 2005 to 2019. The coupling was at a moderate level of coordination. This reflects the rising resilience of China's industrial economy. It is important to continue to optimize structural policies and consolidate the foundation for a stable industrial recovery. The absolute differences between provinces were relatively significant, with poor regional linkages. With respect to location, the east and coastal regions showed increased interaction compared to other regions, and the central region rose in its level of interaction later in the study period. The west was consistently at a disadvantage. China's "four-region strategy" needs to be further implemented, and regional coordination should be further encouraged.

Second, during the study period, the coupling showed spatial imbalance, and was ultimately distributed in alternating strips. This indicates the presence of spatial heterogeneity, and the need for an accurate and coordinated regional development strategy. The highly coordinated area occupied a spatial advantage, and was concentrated along the traffic axis in the southeast. The area with low coordination was concentrated in the northwest. This benign interaction lacked spatial contagion and linkage effects. Breaking down regional barriers and promoting the full flow of elements among regions has become the key to regional coordination.

Third, market consumption, spatial quality, and technological support had a significant positive effect on the coupling of industrial agglomeration and economic resilience. Opening to the outside world through FDI had a negative effect. This highlights the need for scientific and reasonable adjustments according to local conditions, so they can play an appropriate role and promote positive interactions. The opening to the outside world and economic density in the eastern region hinders interaction, and provides a key for scientifically understanding the functional scale of factors. Promoting an open economy and improving the space environment have become a focus for the west. In the northeast, the environment, quality of space, and production efficiency need to be improved. The coastal regions need to strengthen pollution oversight and rationally encourage high-level opening to the outside world. In addition, the inland region should continue to build a new highland for an open economy.

Due to limited data availability, future studies should further explore this topic based on three- or four-digit industrial classifications and case studies. The correlation between different industries could be included in future studies. As big data become more available, such as point of interest (POI) data and traffic travel data, time series data and optimized index selection could be expanded, providing a new way to conduct an in-depth analysis of

regional economic resilience. In addition, it is difficult to quantify other factors that may affect the coupling between the two, such as institutions, culture, and customs. As such, those were not considered in this paper. In the future, the possible impact of these factors should be analyzed using in-depth interviews with subjects of typical and relevant cases.

8.2 Recommendations

Based on this study's results, the following recommendations are made to support the interaction between regional industrial agglomeration and economic resilience. First, policies should be improved to support the resilient development of industries, research investments should be increased, the level of industry linkages should be improved, efficient agglomeration should be promoted, and scale and spillover effects should be implemented. These changes would further advance improvements in regional economic resilience and promote regional integration. Second, it is important to standardize the economic order within the regional agglomeration area, strengthen joint prevention and control, and ensure healthy competition among enterprises. Particular attention should be paid to diversification and agglomeration, maximizing their positive role in enhancing economic resilience. Finally, correctly addressing the scale of the functions of the elements would maximize the synergistic effect of each element. This includes selecting appropriate approaches to improve resilience, actively launching multiple cluster models, breaking through "low-end lock-in," and enhancing the interaction between agglomeration and resilience.

Specifically, the east should apply the power of science and technology, advance green production, strengthen the agglomeration of industrial diversification, build a world-class advanced industrial belt, and improve economic resilience. The west should continue to improve its infrastructure, and introduce technologies and expand markets, to focus on cultivating regional advantages, characteristic industries, and ecological industries. Interactions would strengthen economic resilience by establishing industrial parks. The northeast should increase capital investment, improve production efficiency, and improve industrial supporting policies. The coast should more precisely control environmental pollution and improve the quality of diversified agglomeration. Based on comparative advantages and long-term industrial interests, it is also important to strengthen the synergy between the market and technology, and enhance economic stability. The inland should focus on ecological protection; scientifically and rationally use foreign capital; increase technological expenditures to promote economic sustainability; and achieve regional integrated development.

In conclusion, this research provides a reference for the coupling and synergy of China's industrial agglomeration and regional economic resilience, which supports sustainable economic and high-quality development.

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References

- Bai, L. M., Xiu, C. L., Feng, X. H., Mei, D. W., & Wei, Z. (2019). A comprehensive assessment of urban resilience and its spatial differentiation in China. *World Regional Studies*, 28(6), 77–87.
- Behrens, K., Boualam, B., & Martin, J. (2020). Are clusters resilient? Evidence from Canadian textile industries. *Journal of Economic Geography*, 20(1), 1–36.
- Bishop, P. (2019). Knowledge diversity and entrepreneurship following an economic crisis: An empirical study of regional resilience in Great Britain. *Entrepreneurship & Regional Development*, 31(5), 496–515. <https://doi.org/10.1080/08985626.2018.1541595>
- Boschma, R. (2015). Towards an evolutionary perspective on regional resilience. *Regional Studies*, 49(5), 733–751. <https://doi.org/10.1080/00343404.2014.959481>
- Brown, L., & Greenbaum, R. T. (2017). The role of industrial diversity in economic resilience: An empirical examination across 35 years. *Urban Studies*, 54(6), 1347–1366. <https://doi.org/10.1177/0042098015624870>
- Cainelli, G., Ganau, R., & Modica, M. (2017). Industrial relatedness and regional resilience in the European Union. *Papers in Regional Science*, 98(2), 755–778. <https://doi.org/10.1111/pirs.12377>
- Chen, X. Y. (2019). Economic resilience of industrial clusters. *Entrepreneur Information*, 9, 14–15.
- Chen, Y. W., & Wu, W. K. (2021). Research and analysis on industrial agglomeration, industrial diversification and urban economic resilience. *Science & Technology Progress and Policy*, 38(18), 64–73.
- Doran, J., & Fingleton, B. (2016). Employment resilience in Europe and the 2008 economic crisis: Insights from micro-level data. *Regional Studies*, 50(4), 644–656. <https://doi.org/10.1080/00343404.2015.1088642>
- Eraydin, A. (2016). Attributes and characteristics of regional resilience: Defining and measuring the resilience of Turkish regions. *Regional Studies*, 50(4), 600–614. <https://doi.org/10.1080/00343404.2015.1034672>
- Faggian, A., Gemmiti, R., Jaquet, T., & Santini, I. (2018). Regional economic resilience: The experience of the Italian local labor systems. *Annals of Regional Science*, 60(2SI), 393–410. <https://doi.org/10.1007/s00168-017-0822-9>
- Fahlberg, A., Vicino, T. J., Fernandes, R., & Potiguara, V. (2020). Confronting chronic shocks: Social resilience in Rio de Janeiro's poor neighborhoods. *Cities*, 99, 102623. <https://doi.org/10.1016/j.cities.2020.102623>
- Fan, C. C., & Scott, A. J. (2003). Industrial agglomeration and development: A survey of spatial economic issues in East Asia and a statistical analysis of Chinese regions. *Economic Geography*, 79(3), 295–319. <https://doi.org/10.1111/j.1944-8287.2003.tb00213.x>
- Folke, C., Carpenter, S. R., Walker, B., Scheffer, M., Chapin, T., & Rockström, J. (2010). Resilience thinking: Integrating resilience, adaptability and transformability. *Ecology and Society*, 15(4), 299–305. <https://doi.org/10.5751/ES-03610-150420>
- Fujita, M., & Thisse, J. F. (2005). *Economics of agglomeration: Cities, industrial location, and globalization* (2nd ed.). Cambridge University Press. <https://doi.org/10.1017/CBO9781139051552>
- Galliano, D., & Magrini, M. B. (2015). Triboulet P. Marshall's versus Jacobs' externalities in firm innovation performance: The case of French industry. *Regional Studies*, 49(11), 1840–1858. <https://doi.org/10.1080/00343404.2014.950561>
- Ghouchani, M., Taji, M., Roshan, A. Y., Chehr, M. S., & Hens, L. (2021). Identification and assessment of hidden capacities of urban resilience. *Environment, Development and Sustainability*, 23(3), 3966–3993. <https://doi.org/10.1007/s10668-020-00752-8>
- Guo, Y. T. (2020). *An empirical study on the impact of industry related diversity on urban economic resilience* (pp. 3–36). Jiangxi University of Finance and Economics.
- Han, B. J. (2020). China's economic resilience under the background of COVID-19 epidemic situation. *Theoretical Exploration*, 37(5), 116–121.
- Hao, Y., Gao, S., Guo, Y., Gai, Z., & Wu, H. (2021). Measuring the nexus between economic development and environmental quality based on environmental Kuznets curve: A comparative study between China and Germany for the period of 2000–2017. *Environment, Development and Sustainability*, 23, 16848–16873. <https://doi.org/10.1007/s10668-021-01365-5>
- Hardy, J., Imani, Y., & Zhuang, B. (2018). Regional resilience and global production networks in China: An open political economy perspective. *Competition and Change*, 22(1), 63–80. <https://doi.org/10.1177/1024529417744177>
- He, C. F., & Chen, T. (2019). External demand shocks, related variety and resilience of export. *China Industrial Economics*. <https://doi.org/10.19581/j.cnki.ciejournal.2019.07.004>

- Henry, N., Angus, T., & Jenkins, M. (2021). Motorsport valley revisited: Cluster evolution, strategic cluster coupling and resilience. *European Urban and Regional Studies*, 1, 2–21. <https://doi.org/10.1177/09697764211016039>
- Hu, X. H., & Yang, C. (2019). Institutional change and divergent economic resilience: Path development of two resource-depleted cities in China. *Urban Studies*, 56(16), 3466–3485. <https://doi.org/10.1177/0042098018817223>
- Hu, Z. Q., Miao, C. H., Xiong, X. L., Li, R. Y., & Feng, L. H. (2021). The impact of industrial agglomeration on the industrial resilience of the Yellow River Basin. *Geographical Sciences*, 41(5), 824–831. <https://doi.org/10.13249/j.cnki.sgs.2021.05.010>
- Jordan, M., Chilian, M., & Grigorescu, A. (2015). Regional resilience in Romania: Between realism and aspirations. *Procedia Economics and Finance*, 22, 627–635. [https://doi.org/10.1016/S2212-5671\(15\)00274-9](https://doi.org/10.1016/S2212-5671(15)00274-9)
- Jie, M. H., Shi, N., & Zhang, J. X. (2020). The spatial and temporal differentiation and economic effects of geographical agglomeration of resource-based industries. *Resources and Industry*, 22(5), 19–27.
- Kitsos, A., Carrascal-Incera, A., & Ortega-Argiles, R. (2019). The role of embeddedness on regional economic resilience: Evidence from the UK. *Sustainability*, 11(14), 1–19.
- Li, L. G., Zhang, P. Y., Lo, K., Liu, W., & Li, J. (2020). The evolution of regional economic resilience in the old industrial bases in China: A case study of Liaoning Province, China. *Chinese Geographical Science*, 30(2), 1–12.
- Li, L. G., Zhang, P. Y., Tan, J. T., & Guan, H. M. (2019). Review on the evolution of resilience concept and research progress of regional economic resilience. *Human Geography*, 34(2), 1–7. <https://doi.org/10.13959/j.issn.1003-2398.2019.02.001>
- Liang, Q. (2014). *Space economy: Agglomeration, trade and industrial geography* (pp. 45–123). Science Press.
- Ling, T. Y. (2021). Investigating the malleable socioeconomic resilience pathway to urban cohesion: A case of Taipei metropolitan area. *Environment, Development and Sustainability*, 23, 13016–13041. <https://doi.org/10.1007/s10668-020-01197-9>
- Liu, R., & Zhang, W. J. (2021). Can Spatial agglomeration enhance the resilience of China's manufacturing industry: From the perspective of industrial adaptive structure adjustment. *Contemporary Finance & Economics*, 11, 16–27.
- Liu, W. D. (2020). The impacts of COVID-19 pandemic on the development of economic globalization. *Geographical Research*, 39(7), 1439–1449. <https://doi.org/10.11821/dllyj020200514>
- Liu, Y., Ji, J. H., Zhang, Y. H., & Yang, Y. (2020). Economic resilience and spatial divergence in the Guangdong-Hong Kong-Macao Greater Bay Area in China. *Geographical Research*, 39(9), 2029–2043. <https://doi.org/10.11821/dllyj020200418>
- Lu, J., Chang, H., & Wang, Y. B. (2017). The dynamic evolution of the coupling of regional energy, economy and environment in China. *China Population, Resources and Environment*, 27(2), 60–68. <https://doi.org/10.3969/j.issn.1002-2104.2017.02.010>
- Lu, P., Liu, J., Wang, Y., & Lei, R. (2021). Can industrial agglomeration improve regional green total factor productivity in China? An empirical analysis based on spatial econometrics. *Growth and Change*, 52(2), 1011–1039. <https://doi.org/10.1111/grow.12488>
- Luo, Y. C., Gu, R. X., Wang, C. M., & Xu, S. H. (2015). The spatial effect analysis and influencing factors of industrial agglomeration in counties: Based on the empirical research of the Yangtze River Delta. *Economic Geography*, 35(12), 120–128. <https://doi.org/10.15957/j.cnki.jjdl.2015.12.017>
- Martin, R., & Gardiner, B. (2019). The resilience of cities to economic shocks: A tale of four recessions (and the challenge of Brexit). *Papers in Regional Science*, 98(4), 1801–1832. <https://doi.org/10.1111/pirs.12430>
- Martin, R., Sunley, P., Gardiner, B., & Tyler, P. (2016). How regions react to recessions: Resilience and the role of economic structure. *Regional Studies*, 50(4), 561–585. <https://doi.org/10.1080/00343404.2015.1136410>
- Pei, Y., Zhu, Y. M., Liu, S. X., & Xie, M. L. (2021). Industrial agglomeration and environmental pollution: Based on the specialized and diversified agglomeration in the Yangtze River Delta. *Environment, Development and Sustainability*, 23, 4061–4085. <https://doi.org/10.1007/s10668-020-00756-4>
- Pendall, R., Foster, K. A., & Cowell, M. (2010). Resilience and regions: Building understanding of the metaphor. *Cambridge Journal of Regions, Economy and Society*, 3(1), 71–84. <https://doi.org/10.1093/cjres/rsp028>
- Qiu, B. X. (2018). Resilience city design methods and principles based on complex adaptive system theory. *Urban Development Research*, 25(10), 1–3. <https://doi.org/10.3969/j.issn.1006-3862.2018.10.001>

- Rocchetta, S., & Mina, A. (2019). Technological coherence and the adaptive resilience of regional economies. *Regional Studies*, *53*(9), 1421–1434.
- Shamsuddin, S. (2020). Resilience resistance: The challenges and implications of urban resilience implementation. *Cities*, *103*, 2–10. <https://doi.org/10.1016/j.cities.2020.102763>
- Su, R. G., & Zhao, X. L. (2022). Manufacturing upgrade, information network development and urban economic toughness. *Economy and Management*, *36*(1), 48–57.
- Sun, J. W., Chen, C. J., & Sun, Z. (2022). Study on urban economic resilience and its influencing factors in the Yellow River Basin: From the perspective of different city types. *Economic Geography*, 1–20. <http://kns.cnki.net/kcms/detail/43.1126.k.20220113.1048.002.html>
- Sweeney, B., Mordue, G., & Carey, J. (2020). Resilient or resistant? Critical reflections on resilience in an old industrial region. *Geoforum*, *110*, 125–135. <https://doi.org/10.1016/j.geoforum.2020.02.005>
- Tan, J. T., Hu, X. H., Hassink, R., & Ni, J. W. (2020). Industrial structure or agency: What affects regional economic resilience? Evidence from resource-based cities in China. *Cities*, *106*, 1–11. <https://doi.org/10.1016/j.cities.2020.102906>
- Wang, N., Zhu, Y. M., & Pei, Y. (2021). How does economic infrastructure affect industrial energy efficiency convergence? Empirical evidence from China. *Environment, Development and Sustainability*, *23*(9), 13973–13997. <https://doi.org/10.1007/s10668-021-01247-w>
- Wang, P., & Zhong, M. (2021). Industrial cluster network, technological innovation and urban economic resilience. *Urban Problems*, *8*, 63–71. in Chinese.
- Wang, Y. G., & Gao, J. (2020). Shocks of 2019–nCoV, economic resilience and China's high quality development. *Business and Management Journal*, *42*(5), 5–17.
- Xu, Y., & Deng, H. Y. (2020). Diversification, innovation capability and urban economic resilience. *Economic Perspectives*, *38*(18), 64–73.
- Yu, G. J., He, C. F., & Zhu, S. J. (2020). Industrial cluster resilience: Technological innovation, relational governance, and market diversification. *Geographical Research*, *39*(6), 1343–1356.
- Zhang, K. Y., & He, D. Z. (2020). Spatial classification and spatial selection: The new frontier of agglomeration theory. *Economist*, *256*(4), 36–49.
- Zhang, N. D., & Feng, X. Q. (2019). A comparative study of urban resilience and economic development level of cities in Yangtze River Delta urban agglomeration. *Urban Development Studies*, *26*(1), 82–91. <https://doi.org/10.3969/j.issn.1006-3862.2019.01.017>
- Zhang, Z. (2020). *Study on regional economic resilience in Northeast China* (pp. 87–138). Jilin University.
- Zhang, Z., Li, Z. G., & Hu, X. (2021). Industrial agglomeration, spatial spillover, and regional economic resilience of urban agglomeration. *East China Economic Management*, *35*(8), 59–68.
- Zhao, C. Y., & Wang, S. P. (2021). The impact of economic agglomeration on urban economic resilience. *Journal of Zhongnan University of Economics and Law*. <https://doi.org/10.19639/j.cnki.issn1003-5230.2021.0008>
- Zhu, H. Y., Li, N., Zhuang, Y. H., & Jiang, Z. R. (2021). Resilience characteristics and influencing factors of electronic information industry clusters in the Yangtze River Delta under the impact of crisis. *Geographical Research*, *40*(12), 3420–3436.

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