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Effects of regional integration on industrial green transformation

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Abstract: Based on panel data from 41 cities at or above the prefecture level in the Yangtze River Delta region from 2006 to 2018, the global Moran's I index is used to investigate the spatiotemporal correlation between regional integration and industrial green transformation. Furthermore, the mechanism of regional integration and its impact on industrial green transformation is investigated through spatial Durbin models. It is found that regional integration can promote industrial green transformation through economic scale expansion, industrial structure upgrading, and technological progress, with economic scale as the primary mechanism. Further, results show that both regional integration and industrial green transformation in the Yangtze River Delta exhibit positive spatial autocorrelation, and a significant U-shaped relationship exists between regional integration and industrial green transformation. This indicates that regional integration can significantly promote industrial green transformation only when it surpasses a certain critical threshold. Currently, most cities in the Yangtze River Delta region have approached or surpassed that U-shaped turning point of regional integration. The research findings provide practical insights for the formulation of regional integration strategies and the construction of environmentally sustainable cities in the Yangtze River Delta.

Key words: regional integration; industrial green transformation; spatial Durbin model; Yangtze River Delta region

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China has experienced rapid and continuous urbanization since policy reforms and moves to open the economy began in 1978[1], resulting in significant social and economic growth. Further, these policies have greatly expanded urbanization and increased population density, leading to serious "urban illnesses" such as environmental pollution and ecosystem damage[2]. The industrial sector is the dominant energy consumer and pollution generator in cities and thus plays a crucial role in a green transformation that seeks to reconcile the conflicting goals of rapid economic growth and environmental protection in urban regions[3]. The rapid pace of urbanization in China has produced strong intraregional economic connections that have increased the trend toward regional integration[4]. By offering unique advantages in optimizing resource allocation, industrial restructuring, and technological innovation, regional integration is becoming an important engine of China's economic growth[5]. As the conflict between economic growth and ecological sustainability has intensified in recent years, recent research has focused on the impact of regional integration on environmental quality, offering empirical evidence that regional integration helps to reduce pollution and improve environmental quality. However, few studies investigate both the economic and environmental consequences of regional integration. Industrial green transformation promotes economic growth using an environmentally sustainable approach. As such, using industrial green transformation as a primary research variable corresponds to the need for urban regions to pursue economic development that is green and sustainable.

As one of the most durable economic zones in China, the Yangtze River Delta (YRD) has consistently promoted inter-regional cooperation, which has played a key role in integrated development across China's urban areas for four decades[6]. In addition, the YRD has a strong industrial sector and serves as a pioneer for China's industrial green transformation in addressing the growing conflict between developing an industrial economy and reducing high levels of pollution. In 2018, the industrial added value (IAV) from the YRD accounted for nearly 23% of the IAV of mainland China. Meanwhile, the YRD's industrial wastewater, waste gases, and residues accounted for 32%, 20%, and 15% of the country's total emissions, respectively[7]. Therefore, in assessing the impact of regional integration on industrial green transformation in urban regions, the YRD serves as a strong representative example.

This study examines the relationship between regional integration and industrial green transformation in urban regions, with a particular focus on the spatial effect. First, we examine the spatial-temporal variation trends in regional integration and industrial green transformation in the YRD through an exploratory spatial data analysis method. This allows us to understand the phase character-

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istics of integrated development and industrial green transformation characteristics in the YRD, laying the foundation for subsequent research. Second, we construct a spatial panel model to empirically investigate the influences and mechanisms of regional integration on industrial green transformation. This sheds light on how different levels of regional integration affect industrial green transformation and whether a turning point exists in this relationship. Third, a threshold model is adopted to observe how the influence of mechanism variables on industrial green transformation varies based on promoting regional integration as a long-term strategy. The results have important implications for policymakers by providing insights into the mechanisms through which regional integration can foster sustainable development in urban areas and may inform the design of strategies to promote the green transformation of industrial sectors in similar contexts.

1 Theoretical Hypothesis

Regional integration can facilitate the free flow of economic inputs, such as capital and labor, between regions and improve the efficiency of resource allocation by lowering inter-regional trade barriers[8]. When integration does not dominate regional development, regions tend to encounter a resource mismatch that is often accompanied by distorted price signals. Therefore, industrial enterprises are likely to choose a high-input-high-consumption production mode based on low prices[9], creating problems such as high energy dependence and low-end lock-in, neither of which are conducive to industrial green transformation. In these circumstances, inter-regional relations are dominated by competition for GDP growth rather than synergistic development, as evidenced by issues such as investment competition, duplication of investment in construction, industrial structure convergence, and low energy efficiency[10]. Local protection barriers hinder the process of marketization, which lowers total factor productivity[11] and exacerbates a “race to the bottom” for local environmental regulations, making it difficult to effectively regulate industrial pollution emissions[12]. A low level of regional integration is, therefore, detrimental to industrial green transformation, both economically and environmentally. As a result, we propose the following hypothesis.

Hypothesis 1 The relationship between regional integration and industrial green transformation follows a U-shaped curve, i. e., regional integration can effectively promote industrial green transformation only when it exceeds a certain threshold.

The changes generated by regional integration are not geographically isolated; they affect the inflow and outflow of goods and factors across different areas, creating a closely linked channel of inter-regional cooperation and transmitting local price signals to the surrounding areas. This not only facilitates synergistic economic growth between regions but also promotes technological cooperation and technical innovation spillover for inter-regional enterprises. Green technologies can more easily spread within and across regions through marketization, improving efficiency for industrial enterprises to produce energy savings and reduce emissions[12]. Subsequently, these technologies are transferred to environmental protection industries, creating additional benefits from inter-regional industrial green production. Thus, promoting regional integration may have a beneficial spillover effect on industrial green transformation in the surrounding areas. Therefore, we put forward our next hypothesis.

Hypothesis 2 Regional integration has a positive spatial spillover effect on industrial green transformation.

Based on a review of the literature in related fields, we argue that regional integration can influence industrial green transformation through the following channels.

1) Economic scale. Regional integration fosters economic cooperation that promotes large-scale regional economic expansion, influencing industrial green transformation in both positive and negative ways. On the one hand, large-scale industrial production reduces unit costs of reducing pollution and supports local green production[13]. Moreover, it improves industrial energy efficiency by promoting energy conservation and emission reduction[14]. On the other hand, large-scale economic expansion facilitates spatial industry agglomeration, leading to population-land use conflicts, insufficient infrastructure, and high energy consumption that increases CO_2 emissions and other pollutants[15]. Thus, the mixed impact of regional integration on industrial green transformation through economic scale expansion is determined by these combined effects.

2) Industrial structure. Regional integration hastens the dissolution of market barriers, which prompts the integration of regional resources to optimize and upgrade the industrial structure[16]. Upgrading the industrial structure is a key driver of energy conservation and emission reduction, which is strategically important in transforming industrial production and achieving sustainable competitiveness, thus realizing an industrial green transformation. According to the structural dividend theory, upgrading the industrial structure is a factor in driving productivity growth and enhancing the quality of industrial economic growth[17]. From an environmental perspective, upgrading the industrial structure improves resource utilization efficiency, alleviates ecological constraints on economic development, and reduces environmental pressure from industrial production while still achieving economic growth, thus facilitating industrial green transformation.

3) Technical progress. Regional integration reduces trade and investment barriers by expanding local enterprises’ market base and activities. This intensifies

market competitiveness and encourages R&D directed at technology improvement[8]. Increased knowledge-sharing drives technical progress, specifically with respect to advancements in the efficiency and application of production technology. Technological progress could lead to energy conservation and could reduce emissions in the long term, which contributes to sustainable development[18]. For industrial enterprises, such progress motivates upgrades to production techniques and improvements in organizational processes to reduce pollution and waste. Technological advances also improve energy efficiency by reducing energy extraction, storage, and transportation-related losses[19], supporting a region's industrial green transformation.

In summary, we establish our final hypothesis.

Hypothesis 3 Regional integration can influence industrial green transformation by increasing economic scale, improving industrial structure, and promoting technological progress.

2 Methods, Variable, and Data

2.1 Methods

2.1.1 Global Moran's *I* index

A global version of Moran's *I* index is used to describe the overall spatial distribution state of variables throughout an entire area. The Moran's *I* value is calculated as follows:

$$I = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}(X_i - \bar{X})(X_j - \bar{X})}{\sum_{i=1}^{n}(X_i - \bar{X})\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}} \quad (1)$$

2.1.2 Spatial panel data model

We construct a spatial panel data model to analyze the impact of regional integration on industrial green transformation. Spatial econometric models are classified into three types: the spatial lag model, spatial error model, and spatial Durbin model (SDM)[20]. Among them, the SDM is a general model that accommodates spatial correlations between explanatory variables across regions and the interactive effects of the dependent variable[21], integrating the advantages of the first two types of models. Therefore, the SDM is more suitable for exploring the spatial and spillover effects of regional integration on industrial green transformation. Therefore, we use the SDM as the spatial model in this analysis. To eliminate the influence of heteroscedasticity, the core variables were transformed into a logarithmic scale. The specific econometric expression of the regression model is shown below:

$$G_{it} = \alpha + \rho WG_{jt} + \beta E_{it} + \theta WE_{it} + u_i + v_t + \varepsilon_{it} \quad (2)$$

where G_{it} is industrial green transformation in the i-th city in year t; E_{it} is regional integration in the i-th city in year t; α is the intercept term; β is the influence coefficient of regional integration; ρ and θ are the spatial lag coefficients of industrial green transformation and regional integration, respectively; u_i and v_t represent the fixed effects of city and time, respectively, and ε_{it} is the random disturbance term.

Next, we introduce a quadratic term to describe regional integration to examine whether there is a nonlinear relationship between regional integration and industrial green transformation.

$$G_{it} = \alpha + \rho WG_{jt} + \beta_1 E_{it} + \beta_2 E_{it}^2 + \theta_1 WE_{it} + \theta_2 WE_{it}^2 + u_i + v_t + \varepsilon_{it} \quad (3)$$

where E_{it}^2 is the quadratic term of E_{it}; and β_2 and θ_2 are the coefficient and spatial lag coefficient of E_{it}^2, respectively. The remaining function variables have the same meaning as in Eq. (2).

The selection of spatial weights has a great influence on the estimation results, especially due to the fact that when calculating the spatial spillover effect of regional integration, distance is the important influencing factor on the transboundary degree of economic and environmental factors between regions. Therefore, we use a geographic distance matrix to investigate the spillover effect of core variables. We adopt the square of the distance between cities to represent the weight, i.e., $W_{ij} = 1/d_{ij}^2$. Compared to the spatial distance represented by Euclidean spherical data, the transport distance between cities better reflects objective social and economic realities[22]. Thus, we use railway distance to construct the inverse distance matrix.

2.1.3 Mediating effect model

Referring to the three-step approach in Ref. [23], we introduce three mediating variables, namely economic scale, industrial structure, and technical progress, to construct an incomplete mediating model. The specific goals are as follows: 1) to investigate the impact of regional integration on industrial green transformation, 2) to analyze the influence of regional integration on the mediating variables, and 3) to perform a simultaneous regression of regional integration and the mediating variables on industrial green transformation. The changes in the coefficients and significance of regional integration are assessed to verify whether the mediating effect exists. The coefficients of all three steps must be significant to pass the mediating effect test. The first step is represented by Eq. (2), and the second and third steps are shown as follows:

$$M_{it} = \alpha + \rho WM_{jt} + \beta E_{it} + \theta WE_{it} + u_i + v_t + \varepsilon_{it} \quad (4)$$

$$G_{it} = \alpha + \rho WG_{jt} + \beta_1 E_{it} + \beta_2 M_{it} + \theta_1 WE_{it} + \theta_2 WM_{it} + u_i + v_t + \varepsilon_{it} \quad (5)$$

where M_{it} represents the mediating variables in the i-th city in year t. The remaining variables have the same meaning as in Eq. (3).

2.2 Variable measurement and data sources

2.2.1 Research period and area

Our dataset covers 41 cities at the prefecture level and above in the YRD. Based on data consistency and availability, we use the period from 2006 to 2018 as the research period. The selection of 2006 as the starting year is due to the inconsistency noted in the statistical data of China's seven major consumption goods price indices before and after 2006. We selected 2018 as the end of the investigation period as this was the most recent year for which up-to-date and complete data was available. Relevant data were primarily obtained from the China City Statistical Yearbook (2007—2019), China Price Statistical Yearbook (2007—2019), China Urban Statistical Yearbook (2007—2019), and Statistical Bulletin (2007—2019).

2.2.2 Explanatory variable: Regional integration

In this study, regional integration refers to the integration of economic indicators, i. e., eliminating artificial barriers that can impede an economy's effective operation to promote a more effective allocation of production factors, collaboration, and unity among regional markets. Using the relative price variance method[24], we construct a three-dimensional panel data set ($t \times n \times k$) from time, region, and consumption goods data to calculate the degree of regional integration among individual cities based on the consumer price indexes of nine consumption goods, including food; beverage, tobacco and liquor; garments, shoes and hats; textiles; articles for daily use; cosmetics; traditional Chinese and western medicines; books, newspapers, magazines and electronic publications; fuels.

The steps for calculating regional integration using the relative price variance method are as follows:

1) We produce K relative price indices for the various kinds of consumer goods in city i and city j for year t as P_{it}^k and P_{jt}^k and then calculate the absolute value of their natural logs using the formula $P_{ijt}^k = \ln(P_{it}^k / P_{jt}^k) = | \ln P_{it}^k - \ln P_{jt}^k |$.

2) Since fixed effects related to the specific consumer goods categories can bias the results, we use a de-meaning method to eliminate them, obtaining the residual differences related only to segmentation factors. The de-meaning formula is $\Delta P_{ijt}^k = P_{ijt}^k - \overline{P_t^k}$, where $\overline{P_t^k}$ is the average of all P_{ijt}^k values.

3) We repeat the above steps to calculate the remaining relative price margins for other kinds of goods.

4) We calculate the variance of ΔP_{ijt}^k, i. e., $\mathrm{Var}(\Delta P_{ijt}^k)$. The variances in each administrative unit constitute time series data. This allows us to directly observe the evolution of the variance over time and to test the trend in market integration using the self-moving law of time series. We compute 88 560 relative price variances from the retail price indexes of nine goods in 41 cities over 13 years, from which we obtain 820 (C_{41}^2) groups of paired cities.

5) We combine these relative price variances with data from the same province per year to obtain a market segmentation index for each city (SEG). Finally, we take the square root of SEG's reciprocal to calculate the core variable used in this study, regional integration, then analyze the logarithm of that value using the formula $I_{\mathrm{NT}} = \ln(\sqrt{1/S_{\mathrm{EG}}})$.

Variations in the logarithm of the annual average regional integration for the YRD from 2006 to 2018 are presented in Fig. 1. Overall, regional integration exhibited an upward trend with fluctuations, increasing from 1.34 in 2006 to 1.40 in 2018, which equates to an average annual growth rate of 0.33%. This indicates an increasing flow of resources among cities in the YRD during the investigation period, fostering greater market integration and economic development synergies among those cities. By dividing the study period into three stages, we can observe typical temporal patterns in regional integration in the YRD.

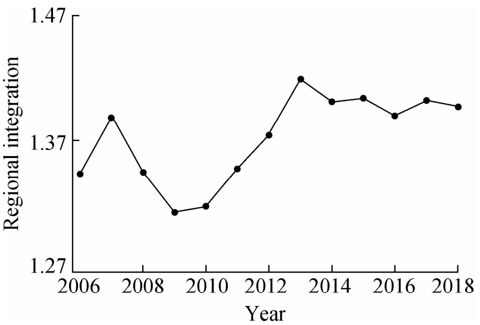

Fig. 1 Annual average level of regional integration in the Yangtze River Delta from 2006 to 2018

1) Adjustment stage (2006—2009): This stage witnessed an initial increase in 2006—2007. However, this growth was immediately followed by a rapid decline in 2007—2009 due to the impact of the global financial crisis. The crisis led to a fragmented and uneven pattern of economic development across different regions within the YRD.

2) Development stage (2009—2013): Regulatory authorities in the three provinces and one municipality in the YRD signed a memorandum of cooperation and exchange during this period. This initiative improved the mechanisms for market cooperation, clarified the direction and priorities for market cooperation, and promoted sustained development of regional integration. During this stage, the average annual growth rate of regional integration was 2.00%, reaching its highest level in 2013.

3) Improvement stage (2013—2018): Regional integration gradually converged to a regular fluctuating pat-

tern, with the average level remaining close to a relatively high level of 1.40.

2.2.3 Dependent variable: Industrial green transformation

Industrial green transformation is a dynamic and comprehensive process involving the development and transformation of an entire industrial value chain with an emphasis on resource conservation and environmental friendliness. Thus, a synthetic indicator designed to reflect this transformation must include multiple perspectives. Based on the definition of industrial green transformation and referring to previous findings in Ref. [25], we select nine indicators to construct a comprehensive evaluation metric as our dependent variable using the following five inputs: resource utilization, pollution emission, clean development, production efficiency, and sustainable development (see Tab. 1). To avoid introducing subjective factors or objective constraints into the metric, the entropy method is used to assign weights to each index. The entropy method overcomes problems of randomness and speculation that subjective weightings cannot avoid and effectively resolves the problem of overlapping information among multiple indexes.

Tab. 1 Comprehensive evaluation of industrial green transformation

Main index	Minor index	Calculation	Direction	Weight
Resource utilization	Industrial energy consumption	Energy consumption per unit of industrial added value	Negative	0.050
	Industrial water consumption	Water consumption per unit of industrial added value	Negative	0.032
Pollution emission	Industrial carbon emissions	Carbon dioxide emission per unit of industrial added value	Negative	0.098
	Industrial sulfur dioxide emissions	Sulfur dioxide emissions per unit of industrial added value	Negative	0.075
	Industrial wastewater emissions	Industrial wastewater discharge per unit of industrial added value	Negative	0.060
Clean development	Clean development of industrial structure	Ratio of the output value of energy-intensive industries to industrial added value	Negative	0.086
Production efficiency	Industrial productivity	Total factor productivity calculated by data envelopment analysis	Positive	0.406
Sustainable development	Comprehensive utilization of solid waste	Comprehensive utilization-production of solid waste ratio	Positive	0.121
	Comprehensive utilization of industrial hazardous waste	Comprehensive utilization-production of hazardous waste ratio	Positive	0.072

2.2.4 Control variables

Based on the relevant literature, we select the following independent variables that may affect the dependent variable: 1) Government expenditures (N), measured as the ratio of a government's general public budget expenditures to GDP; 2) Foreign direct investment (F), expressed as the proportion of foreign direct investment in local GDP; 3) Trade openness (T), measured as the ratio of total regional import and export trade to GDP (converting USD to RMB); and 4) Industrial development (S), expressed as the ratio of IAV to regional GDP (the higher the ratio is, the better the quality and benefits of regional industrial development will be).

2.2.5 Mediating variables

As discussed above, the mediating variables in our model are economic scale, industrial structure, and technical progress. We measure them as follows: 1) Economic scale (M_1) is the logarithm of GNP per capita; 2) Industrial structure (M_2) is measured as the ratio of output values between tertiary and secondary industry, reflecting the process of the industrial structure moving from low to high; 3) Technical progress (M_3) calculated using the DEA-based Malmquist index method[26], with capital stock and the number of employees as the input variables and IAV as the output variable.

To account for heteroscedasticity, we use the logarithms of the core variables. Time and individual fixed effects are also controlled to mitigate the influence of unobservable factors. Descriptive statistics of the main variables are presented in Tab. 2.

3 Results and Discussion

3.1 Spatial correlation test

Tab. 3 shows the global Moran's I index values for regional integration and industrial green transformation in the YRD from 2006 to 2018 based on the inverse distance matrix. The global Moran's I value for regional integration is significantly positive at the 1% level, indicating a significant positive spatial correlation of regional integration in the YRD. The Moran's I value of regional integration exhibits yearly variations ranging from 0.227 to 0.571 in a wavelike pattern, which was lower from 2006 to 2011 but gradually increased from 2012 to 2018. This

Tab. 2 Descriptive statistics of the main variables

Variables	Count	Mean	Std	Min	Max
Regional integration E	533	1.33	0.10	1.01	1.54
Industrial green transformation G	533	1.21	0.24	0.44	1.74
Economic scale M_1	533	6.79	0.97	4.87	9.42
Industrial structure M_2	533	0.94	0.32	0.32	2.34
Technical progress M_3	533	0.56	0.22	0.06	1.00
Government expenditure N	533	0.12	0.08	0.02	0.48
Foreign direct investment F	533	0.03	0.03	0.00	0.19
Trade openness T	533	0.06	0.08	0.00	0.83
Industrial structure S	533	0.48	0.22	0.15	2.49

indicates that the spatial clustering of regional integration in the YRD strengthened in the later years of the period, and a higher positive spatial diffusion effect was observed.

The global Moran's I value for industrial green transformation was also significantly positive during the investigation period, except in 2006. The Moran's I value of industrial green transformation ranged from 0.076 to 0.302, indicating a positive spatial diffusion effect of industrial green transformation in the YRD. The average Moran's I for industrial green transformation in the second half of the period studied is higher (0.26) than in the first half (0.17), suggesting an increasing trend of spatial autocorrelation in the latter part of the study period. Thus, we conclude that the spatial clustering of regional integration and industrial green transformation in the YRD strengthened over time, with a higher positive spatial diffusion effect observed in recent years.

Tab. 3 Global Moran's I value of regional integration and industrial green transformation in the Yangtze River Delta from 2006 to 2018

Year	2006	2007	2008	2009	2010	2011	2012
E	0.222**	0.299**	0.252***	0.227*	0.571***	0.460***	0.299***
G	−0.001	0.108**	0.076**	0.228***	0.246***	0.183***	0.168**
Year	2013	2014	2015	2016	2017	2018	
E	0.340***	0.386***	0.387**	0.392**	0.394**	0.401**	
G	0.289***	0.218*	0.254**	0.251***	0.302**	0.274**	

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

3.2 Benchmark regression

An appropriate model must be selected before conducting the empirical test. The results of the Wald and LR tests indicate that SDM can provide more accurate estimation results. The coefficients of the Hausman test are significant at the 1% level, which rejects the null hypothesis of random effects. Therefore, we adopt the SDM with bidirectional fixed effects of individual and time controlled for the regression. Tab. 4 reports the regression coefficients based on Eqs. (3) and (4) using the geographic adjacency matrix.

The regression results based on Eq. (2) show that regardless of the control variables, the coefficient of E is significantly positive at the 5% level. This indicates that an increase in the level of regional integration can effectively promote industrial green transformation. The coefficient of the spatial lag term of regional integration (WE) is also significantly positive at the 5% level, indicating that improvements in regional integration can promote industrial green transformation of adjacent cities at the economic geography level. Furthermore, the spatial lag coefficients (spatial rho) are all significantly positive, indicating that industrial green transformation in the YRD region exhibits significant spatial clustering. In other words, one city's industrial green transformation is closely related to that of adjacent cities in terms of economic geography, reflecting the saying "near vermilion, near ink[27]." According to the regression results from Eq. (3), the coefficients of E and E^2 are significantly negative and positive, respectively, indicating a positive U-shaped nonlinear relationship between regional integration and industrial green transformation. When regional integration is below a certain level, its lack of development will inhibit industrial green transformation; regional integration can significantly promote industrial green transformation only when it surpasses a critical threshold. Our calculations show this critical threshold is 1.39, and the mean value of regional integration in 2017 is 1.40, indicating that the integrated regional development of most cities in the YRD is close to or slightly beyond the turning point of stimulating industrial green transformation.

Regarding the control variables, the effects of T are positive but insignificant due to the YRD's large share of processing trade. The export of pollution-intensive industries in the YRD leads to environmental degradation, and the offsetting negative effects of environmental pollution from increasing trade make its impact on industrial green transformation insignificant. F and N have significant positive effects but negligible spillover effects, meaning that government funding and foreign investment in the YRD can promote local industrial green transformation but have no discernible effect on neighboring cities. S has a strong positive effect but considerable negative spillover effects, indicating that industrial development benefits local industrial green transformation but not the surrounding regions due to highly polluting industries being relocated to nearby areas. The industrial pollution in Shanghai and Jiangsu provinces in the YRD exhibit such characteristics[28], impairing their ability to upgrade to cleaner industrial production methods and hindering their industrial green transformation.

Tab. 4 Benchmark regression of regional integration affecting industrial green transformation

Variables	Eq. (2)		Eq. (3)	
	Without control variables	With control variables	Without control variables	With control variables
E	0.293** (2.71)	0.259** (2.63)	−1.203** (−2.54)	−1.180** (−2.37)
WE	2.437** (2.33)	2.404** (2.27)	−1.051** (−2.68)	−1.058** (−2.19)
E^2			0.433*** (3.31)	0.424*** (3.31)
WE^2			3.414*** (3.64)	3.112*** (3.56)
N		0.167*** (4.45)		0.187*** (3.12)
WN		−0.002 (−0.28)		−0.002 (−0.16)
F		0.122** (2.48)		0.124** (2.53)
WF		0.014 (1.02)		0.015 (1.06)
T		0.045** (2.07)		0.047** (2.02)
WT		0.011 (0.86)		0.009 (0.88)
S		0.037* (1.89)		0.041* (1.78)
WS		−0.070** (−2.20)		−0.072** (−2.14)
Spatial rho	0.480** (2.82)	0.493** (2.63)	0.427** (2.78)	0.445** (2.71)
Time effects	Yes	Yes	Yes	Yes
City effects	Yes	Yes	Yes	Yes
R^2 overall	0.795	0.796	0.793	0.802
Log-likelihood	415.068	421.227	412.507	419.634
Obs	533	533	533	533

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. *Z* statistics are reported in parentheses.

3.3 Mediating effect analysis

This section explores the mechanism of regional integration and its influence from three aspects: economic scale (M_1), industrial structure (M_2), and technological progress (M_3) through the incomplete mediation model. The results of mediation effect tests based on Eqs. (2), (4), and (5) are shown in Tab. 5.

Tab. 5 Mediating effect test

Variables	Test 1			Test 2			Test 3		
	Eq. (2)	Eq. (4)	Eq. (5)	Eq. (2)	Eq. (4)	Eq. (5)	Eq. (2)	Eq. (4)	Eq. (5)
E	−0.166** (−2.28)	0.673*** (7.64)	−0.157* (−1.66)	−0.166** (−2.28)	0.170* (1.82)	−0.104* (−1.76)	−0.166** (−2.28)	0.043*** (3.62)	−0.127* (−1.95)
WE	0.169** (2.80)	0.763** (2.71)	0.416** (2.43)	0.169** (2.80)	0.751 (1.28)	0.595* (1.91)	0.169** (2.80)	0.413** (2.30)	0.761** (2.11)
M_1			0.203** (2.58)						
WM_1			−0.024** (−2.76)						
M_2						0.044** (2.11)			
WM_2						0.031* (1.81)			
M_3									1.314*** (36.56)
WM_3									0.465*** (8.32)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.637	0.449	0.776	0.637	0.514	0.838	0.637	0.741	0.800
Obs	533	533	533	533	533	533	533	533	533

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. *Z* statistics are reported in parentheses.

In Test 1, the positive coefficient of *E* suggests that regional integration promotes economic scale expansion. This effect remains significant even after controlling for economic scale, indicating that economic scale acts as a mediating variable in the relationship between regional integration and industrial green transformation. The analysis shows that the economic scale has a significant mediating effect of 0.136. The results of Test 2 reveal that regional integration promotes upgrades to the industrial structure, with a significant positive coefficient for *E*. This effect remains significant even after controlling for the indirect effect of industrial structure, suggesting that industrial upgrading can partially offset the negative effect of regional integration before the threshold value is reached. The mediating effect of industrial structure is 0.010. Similarly, Test 3 shows that technical progress acts as a positive mediating variable in the relationship between regional integration and industrial green transformation, with a mediating effect of 0.058. These findings confirm Hypothesis 3. Market size clearly has the greatest mediating effect in the process by which regional integration influences industrial green transformation, as it is greater than the combined effects of industrial structure and technological progress.

The spatially lagged terms of M_2 and M_3 are notably positive, demonstrating that both local industrial structure upgrading and technological progress have a positive spillover effect on industrial green transformation in the surrounding areas. The spatially lagged term of M_1 is significantly negative, indicating that the expanding local market scale is not conducive to industrial green transformation in the surrounding cities, probably because the agglomeration effect generated by one city's increased economic scale could interfere with the free flow and efficient allocation of high-quality production factors to the surrounding areas. The spillover effect of market size is less than the sum of the spillover effects of industrial structure and technological progress, demonstrating that regional integration has a positive spatial spillover effect on industrial green transformation in general.

4 Conclusions

1) The YRD shows a significant positive spatial correlation and clustering of regional integration and industrial green transformation during the study period. The spatial clustering of regional integration and industrial green transformation strengthened over time, with a higher positive spatial diffusion effect observed in the later years of the study period.

2) There is a U-shaped relationship between regional integration and industrial green transformation, indicating that regional integration can significantly promote industrial green transformation only when it surpasses a certain critical threshold. Currently, most cities in the YRD have crossed that inflection point, meaning that regional integration can support industrial green transformation. Regional integration has a positive spillover effect on adjacent areas, but the effect diminishes with increasing spatial distance between cities.

3) Regional integration has the potential to facilitate industrial green transformation through economic scale expansion, industrial structure upgrading, and technological progress. Economic scale expansion has the largest mediating effect, which is greater than the sum of the effects of industrial structure and technological progress. Furthermore, the spillover effects of upgrading the local industrial structure and technological progress on industrial green transformation in the surrounding areas are positive. However, expanding the local market scale is not conducive to industrial green transformation in the surrounding cities.

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区域一体化对工业绿色转型的影响

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摘要:基于2006—2018年间长江三角洲地区41个地级及以上城市的面板数据,采用全局莫兰指数探究了区域一体化和工业绿色转型的时空相关性,并通过空间杜宾模型研究了区域一体化对工业绿色转型的影响效应和作用机制.研究结果显示:长江三角洲地区的区域一体化和工业绿色转型都呈现出正向空间自相关性;区域一体化和工业绿色转型之间存在显著的U形关系,只有当区域一体化超过某一临界值时,才能显著促进工业绿色转型;目前,长三角地区的大多数城市已经接近或超过了区域一体化的U形拐点;区域一体化可以通过经济规模扩大、产业结构升级和技术进步来促进工业绿色转型,其中经济规模是当前的主要作用机制.研究结果可为长三角地区的区域一体化发展战略和生态文明建设提供实际参考.

关键词:区域一体化;工业绿色转型;空间杜宾模型;长江三角洲

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