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Research Article

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Research on the coordination characteristics and interaction between innovation-driven development and green development of the Yangtze River Economic Belt in China

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Abstract: Innovation-driven development and green development are both important ways to achieve regional sustainable development. Many studies have focused on innovation-driven dynamic factors and green development impact factors, yet most have paid little attention to the relationship between the two types of factors. This study considers the innovation-driven development and green development evaluation systems of 130 cities in the Yangtze River Economic Belt. Through expert group evaluation, the three dimensions of green production, green life and green ecology are selected to represent the green development index. Innovation input, innovation performance, and innovation potential reflect the innovation-driven development index. The entropy TOPSIS method is used to measure the innovation-driven development index and the green development index of 130 cities in the Yangtze River Economic Belt. Then, a coupling coordination evaluation model and a spatiotemporal heterogeneity analysis model are constructed to discuss the coupling coordination index of regional innovation-driven development and green development in the Yangtze River Economic Belt and to determine its temporal and spatial distribution characteristics. Finally, we choose a spatial panel regression model to explore the relationship between the innovation-driven development index and the green development index of the Yangtze River Economic Belt. The research results show that there is a significant difference between the innovation-driven development index and the green development index of the 130 cities in the Yangtze River Economic Belt in terms of the temporal and spatial distribution. The coordination index of the two has an imbalanced distribution feature, and there is a significant direct or indirect relationship between the two structural indicators in a mathematical sense. This study enhances the academic community's understanding of the interaction between innovation-driven development and green development, provides scientifically based support for green development, offers guidance for the implementation of innovation capabilities, and ultimately supports a policy design facilitating regional sustainable development.

Keywords: innovation-driven development; green development; coupling and coordination; panel model

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1 Introduction

Innovation-driven development is an important development method for the world economy in the 21st century. It promotes the transformation and development of the economy from a focus on resource agglomeration and environmental pollution to a focus on resource-saving and environmentally friendly production (Yang and Huang 2019). Innovation-driven development leads to the transformation from the traditional economy, which relies on resource input to promote economic growth, to an economy that relies on scientific and technological changes and labour productivity increases to promote the two-way improvement of the economy in terms of quantity and quality. Most innovation-driven studies focus on innovation-driven economic development methods, paths, and effects, and they rarely consider innovation-driven impact factors. The analysis of the relationship between impact factors on innovation is conducive to further improving the regional innovation level and optimizing innovation-driven performance (Yang and Yan 2019).

Green development is an important approach to regional sustainable development and the main means to solve problems linked to economic development, resources and environment in the 21st century (Zhao et al. 2010). While promoting the further improvement of the regional economy, green development needs to consider the sustainable use of resources and the improvement of environmental protection quality. The current academic research on green development mainly focuses on the evaluation of the level of green development, the action mechanism and implementation approaches to environmental factors, while the research on the relationship between green development and the driving factors of green development is relatively insufficient. This paper studies the interaction between green development and innovation from the perspective of innovation-driven development, aiming to promote a virtuous cycle of innovation-driven, green economic development and provide a new impetus for regional green development.

Innovation-driven development is one of the important driving forces of regional green economic development. The improvement in the green development level feeds back to the supply of innovation-driven factors, and there is an interactive relationship between the two factors under spatiotemporal constraints (Feng and Chen 2018). Both innovation-driven development and green development are composed of complex elements, and the synergistic mechanism between them is reflected in the interaction between elements and in the interaction between elements and the whole. However, the existing literature studies on innovation-driven development and green development are limited to the general relationship between innovation-driven development and green development (Chen et al. 2016a) and lack local understanding. Only by deeply analysing the local and overall relationship between innovation-driven indicators and the green development index can we implement a specific path supporting the synergetic relationship between innovation-driven development and green development.

Therefore, by comprehensively measuring the innovation-driven development index and green development index in the case of the Yangtze River Economic Belt, this article uses the coupling coordination model to explore the coordinated development of the two spatiotemporal patterns and finally analyses the spatial mechanism of the innovation-driven development index and the green development index through the spatial panel model. This effort provides a basic reference for the innovation-driven model and the green development model of regional sustainable development and promotes the further expansion of the research paradigm of regional sustainable development.

2 Literature review

2.1 Innovation-driven development

Innovation-driven development relies on the social and economic benefits brought by scientific and technological innovation to realize the intensive growth mode, and the core aim is to improve the productivity of production factors by using technological change (Alheet and Hamdan 2020; Laužikas and Dailydaitė 2014). In the 21st century, innovation is the primary driving force for world economic development, a strategic support for building a modern economic system, and the only way to achieve high-quality development (Cao et al. 2019). The academic research on innovation-driven development has a long history. The research focus has been extended from the initial productivity improvement driving economic development to recent changes in production methods and production technologies that have brought economic growth, resource conservation, environmental protection and other multidimensional benefits, and the connotations of innovation-driven development have been constantly enriched (Calignano and Trippl 2020; De Marchi 2012; Mensah et al. 2018; Yan et al. 2018). Second, in terms of evaluating the innovation-driven index, education level or productivity level has taken as the core index of the innovation-driven index in the last century. Recently, result assessment indicators, such as innovation performance, have been added, and the evaluation system has gradually tended to focus on comprehensiveness, integrity and fairness (Abdelkafi and Pero 2018; Fei et al. 2020; Zhang and Li 2020).

2.2 Green development

Green development is currently the best form of social and economic development, reflecting the harmonious symbiosis between human society and the natural environment (Chen et al. 2019). From ancient times to the present, the survival and development of human beings have been closely related to the natural environment, and human production and lifestyles have led to profound changes in the natural environment. The focus on green development in academic studies started with the industrial revolution. With the rapid development of industry, the earth's environment has been constantly deteriorating, and the living space of human beings is threatened. Therefore, the concept of green development has attracted the attention of all humankind (Song et al. 2016). Green development is a harmonious mode of development between humans and the land. Its core significance is to realize the unity of human social development and environmental protection. Scholars have studied the course of green development, from the reduction of the discharge of industrial wastewater, waste gas, and waste residue to the transformation of production methods (Burnett et al. 2013), and studies of the connotation and extension of green development are gradually expanding from the main focus on industrial production to the integrated development of production, life and ecology (Craig 2018; He et al. 2019; Yuan et al. 2020). Currently, scholars consider how to achieve a high-quality green development mode and what social, economic and ecological benefits are generated by green development (Fan et al. 2019; Li and Wu 2017; Wang and Shao 2019).

2.3 Innovation-driven development and green development

In addition to facing the shortcomings of traditional development, green development requires innovative development methods to achieve the integration and unity of socioeconomic development and ecological environmental protection (Meirun et al. 2021). Innovation-driven development is a technological means to realize the transformation of the development mode. Scholars have studied the relationship between innovation and green development from the perspective of diversified innovations. At the beginning, productivity can be improved to reduce the emission of environmental pollutants, and in this period, the relationship between industrial production and environmental pollution is the main focus of attention (Li et al. 2019b). In the middle stage of industrialization, the level of productivity is greatly improved, and the research on innovation-driven development and green development focuses on the role of the improvement in science and technology and the treatment rate of environmental pollution (Chen et al. 2016b; Ghisetti and Quatraro 2017; Shao et al. 2016; Yuan and Xiang 2018; Zhang et al. 2018). In the later stages of industrialization, human material levels are mainly satisfied. The restoration of the ecological environment becomes a new pursuit of human quality of life, and innovation is mainly applied in the field of ecological environment restoration (Chen 2015; Li et al. 2019a; Sotarauta and Suvinen 2019).

2.4 Current deficiencies and improvements

Innovation-driven development, green development and their interaction have not received enough attention in the following aspects. (1) Studies on innovation-driven development have focused too much on the analysis of the drivers of results, such as what innovation-driven measures are adopted and what development achievements are obtained, but have placed little emphasis on the influence of various factors on innovation and the interaction between innovation and achievements. This paper intends to elaborate on the relationship between innovation drive and innovation achievement from the three aspects of green life, green ecology and green production. (2) While focusing on the social, economic and ecological benefits of green development, previous studies have neglected the dynamic mechanism of maintaining green development. The sustainable and stable driving force of green development is the power source for realizing the sustainable development of humankind. This paper aims to explore the relationship between green development and driving forces from three aspects: innovation input, innovation performance and innovation potential. (3) Academic studies on the relationship between innovation-driven development and green development have paid more attention to the overall connection than to the mechanism of action between the two structures. However, the composition structure is the basis for analysing the mechanism of action between innovation-driven development and green development and the focal point for implementing the optimization path. Therefore, this paper explores the contribution of details to overall progress by breaking down the components of innovation-driven development and green development.

3 Analysis framework

The above literature review shows that there is a significant direct or indirect relationship between innovation-driven development and green development in different periods, and this mechanism has not been addressed in previous studies. We have established a complete set of evaluation processes, as shown in Figure 1. The evaluation is divided into three parts. The first part is the comprehensive evaluation (blue arrow). Through the construction of an evaluation index system, the innovation-driven development index and green development index are comprehensively evaluated at the functional and structural levels. The second part is the coordination evaluation (red arrow). The coupling coordination model is used to explore the coordination relationship between innovation-driven development and coordinated development, and the spatial agglomeration and anomalous distribution characteristics of the coupling coordination index are analysed based on a spatial-temporal heterogeneity model. The third part is impact assessment (yellow arrow). In this part, the dimension of the interaction between innovation-driven and green development is reduced to the level of specific indicators, and the positive and negative properties and the strength of the impact factors of innovation-driven development and green development are explored. Finally, on the basis of the above three research conclusions, the paper proposes policy suggestions to promote regional innovation-driven development and green development.

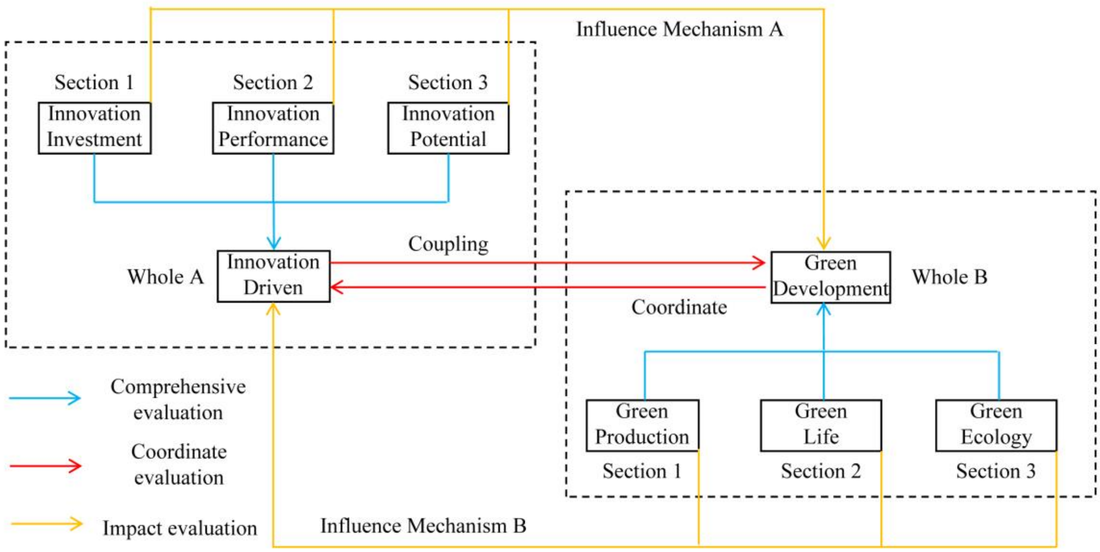

Fig. 1 Coordinated analysis framework of innovation-driven development and green development in the Yangtze River Economic Belt

4 Data sources and research methods

4.1 Study area and dataset

Located in southern China, the Yangtze River Economic Belt covers 11 provinces and cities (Shanghai, Jiangsu, Zhejiang, Anhui, Jiangxi, Hubei, Hunan, Chongqing, Sichuan, Yunnan and Guizhou) from east to west (Figure 2a). The 11 provinces and cities include 130 cities, such as Shanghai, Nanjing, Wuhan and Chongqing (Figure 2B), covering an area of approximately 2.05 million km^2 and representing more than 40% of China's population and GDP. The Yangtze River Economic Belt is a giant river basin economic belt with the largest population, the largest industrial scale and the most complete urban system in the world.

The statistical data used in this analysis come from the 2004, 2011 and 2018 China City Statistical Yearbooks (http://www.stats.gov.cn/tjsj/); the administrative division map of the Yangtze River Economic Belt was downloaded and drawn from the standard map service system website of the Ministry of Natural Resources of China (http://bzdt.ch.mnr.gov.cn/) for spatial analysis.

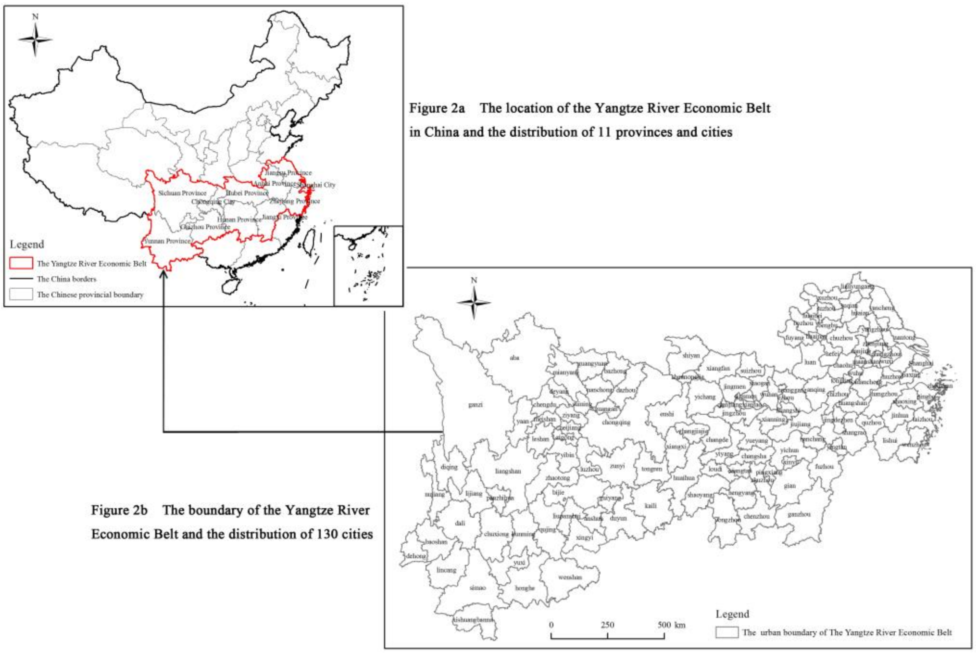

Fig. 2 Location diagram and city composition of the Yangtze River Economic Belt in China

4.2 Evaluation index system

Following the principles of representativeness, comparability, hierarchy and operability and referring to relevant literature (Li and Song 2016; Sun et al. 2018; Wang et al. 2018; Wang et al. 2019b; Yin et al. 2014) and experts' opinions, an innovation-driven development and green development evaluation system for the Yangtze River Economic Belt was established, as shown in Table 1. The green development index provides a comprehensive evaluation from three levels: green production, green life and green ecology. Production, life and ecology include all the behavioural characteristics relevant to regional socio-economic development and the natural environment. The green behaviour reflected by these three factors can basically represent the level of regional green development. Innovation-driven development refers to the innovation input, innovation performance and potential of the three dimensions, representing the characteristics of innovation activity based on inputs and highlighting innovation as the driving force of the social and economic development of the whole process.

Table 1 Evaluation index system for innovation-driven development and green development

Target	Type	Index	Code	unit	Attribute
Green Development	Green Production	Industrial wastewater discharge per ten thousand yuan of industrial output value	FS	Ten thousand tons	Negative
		Industrial sulfur dioxide emissions per ten thousand yuan of industrial output value	FL	Ton	Negative
		Industrial smoke (dust) emissions per ten thousand yuan of industrial output value	FF	Ton	Negative

	Green Life	Domestic sewage treatment rate	WS	%	Positive
		Domestic natural gas penetration rate	WR	%	Positive
		Harmless treatment rate of domestic garbage	WL	%	Positive
	Green Ecology	Park area per capita	PG	Square meter	Positive
		The percentage of days with good air in the whole year	YK	%	Positive
		Surface water at or better than Ⅲ class water percentage	GP	%	Positive
Innovation-Driven Development	Innovation Investment	ten thousand yuan GDP technology expenditure	KZ	yuan	Positive
		R&D expenditure as a proportion of GDP	KB	%	Positive
		Number of R&D personnel per ten thousand people	KR	people	Positive
	Innovation Performance	Number of patent applications per person in science and technology	ZS	Pieces	Positive
		Energy consumption per ten thousand yuan GDP	NH	Tons of standard coal	Positive
		Patent application authorization rate	ZD	%	Positive
	Innovation Potential	ten thousand yuan GDP education expenditure	JZ	yuan	Positive
		Number of college students per ten thousand people	CS	people	Positive
		Number of education employees per ten thousand people	EP	people	Positive

4.3 Research methods

4.3.1 Comprehensive index evaluation

Considering the difference in weights between the innovation-driven development and green development evaluation indexes, the entropy weight TOPSIS method (Freeman et al. 2015) is applied for comprehensive evaluation and analysis. This method uses the technique of approaching the ideal solution to determine the order of the evaluation objects. The calculation steps are as follows:

1) Assume that there are m evaluation objects, and each object has n evaluation indexes. Based on this, the judgement matrix is constructed as Equation (1):

$$X = (x_{ij})_{m\times n}(i = 1,2,\cdots, m; j = 1,2,\cdots, n) \tag{1}$$

2) Standardize the judgement matrix:

The positive index and negative index are shown as follows:

$$x_{ij}^{'} = \frac{x_{ij} - \min(x_{ij})}{\max(x_{ij}) - \min(x_{ij})} \tag{2}$$

$$x_{ij}^{'} = \frac{\max(x_{ij}) - x_{ij}}{\max(x_{ij}) - \min(x_{ij})} \tag{3}$$

3) Calculate information entropy:

$$H_j = -k\sum_{i=1}^{m} p_{ij} \ln p_{ij} \tag{4}$$

where $p_{ij} = \frac{x_{ij}^{'}}{\sum_{i=1}^{m} x_{ij}^{'}}$; $k = \frac{1}{\ln m}$.

4) Determine the weight of index j:

$$w_i = \frac{1 - H_i}{\sum_{j=1}^{n}(1 - H_j)} \tag{5}$$

where $w_j \in [0,1]$, $\sum_{j=1}^{n} w_j = 1$.

5) Calculate the weighted matrix:

$$R = (r_{ij})_{m\times n}, r_{ij} = w_j \times x_{ij}(i = 1,2,\cdots, n) \tag{6}$$

6) Determine the optimal solution S_j^+ and worst solution S_j^-:

$$S_j^+ = \max(r_{1j}, r_{2j},\cdots,r_{nj}), S_j^- = \min(r_{1j}, r_{2j},\cdots, r_{nj}) \tag{7}$$

7) Calculate the Euclidean distance between the optimal solution and the worst solution of each scheme:

$$sep_i^+ = \sqrt{\sum_{j=1}^{n}(s_j^+ - r_{ij})^2}, sep_i^- = \sqrt{\sum_{j=1}^{n}(s_j^- - r_{ij})^2} \tag{8}$$

8) Calculate the comprehensive evaluation index:

$$C_i = \frac{sep_i^-}{sep_i^+ + sep_i^-}, C_i \in [0,1] \tag{9}$$

In the formula, the larger the value of C_i is, the better the evaluation object.

4.3.2 Coordinated development evaluation

The coupling coordination model in physics is used for reference (Wang et al. 2019a) to establish the coupling coordination evaluation model of innovation-driven development and green development in the Yangtze River Economic Belt, and the calculation formula is as follows:

$$OU = \left\{\frac{IDA \times GDL}{(\frac{IDA + GDL}{2})^2}\right\}^2 \tag{10}$$

where OU is the coupling degree between innovation-drive development and green development, which is between $[0-1]$; IDA is the innovation-driven composite index; and GDL is the green development composite index. The greater the value of OU is, the stronger the interaction between innovation-driven development and green development; otherwise, the weaker the interaction.

The coupling degree indicates the degree of correlation between the systems but cannot represent the ranking relationship. The coordination degree model (Wang et al. 2019a) is adopted to evaluate the level of coordination between innovation-driven development and green development. The calculation formula is as follows:

$$XE = \sqrt{OU \times ZHZ} \tag{11}$$

In the formula, XE is the degree of system coordination and OU is the degree of system coupling. The value of XE ranges from $[0-1]$, and ZHZ is the weighted average of the innovation-driven index and the green development index. The larger the value of XE is, the higher the degree of coordination between innovation-driven development and green development, and vice versa.

4.3.3 Analysis of influencing factors

The traditional panel econometric model ignores the effect of spatial parameters on the regression results. This article combines the spatial panel regression model (Wang et al. 2016) and provides regression results that are more consistent with reality by including the relationship between spatial units of the Yangtze River Economic Belt in the econometric model. The spatial lag model, spatial error model and spatial Durbin model are adopted to reflect the spatial interaction relationship between the impact factors on the innovation-driven capacity and the green development level of the Yangtze River Economic Belt. The model can be set as:

$$GGAQ_{it} = \beta X_{it} + \rho \sum_{j=1}^{N} W_{ij} GGAQ_{jt} + \theta \sum_{j=1}^{N} W_{ij} X_{jt} + \mu_i \tag{12}$$

$$\mu_i = \lambda W \mu + \varepsilon_i \tag{13}$$

where $GGAQ_{it}$ is the innovation-driven index or green development index, i and j represent different regions of the Yangtze River Economic Belt, W_{ij} is the spatial matrix of $N \times N$, X_{it} is the dependent variable, λ is the spatial error regression coefficient, ρ is the spatial regression coefficient of the dependent variable, β is the regression coefficient vector of the explanatory variable, θ is the spatial regression coefficient of the independent variable, and ε_i is the random error term.

When $\rho \neq 0$ and $\theta = 0$, equation (12) is transformed into a spatial lag model:

$$GGAQ_{it} = \beta X_{it} + \rho\sum_{j=1}^{N} W_{ij} GGAQ_{jt} + \mu_i \tag{14}$$

When $\lambda \neq 0$ and $\rho = 0$, equation 2.13 is transformed into a spatial error model:

$$GGAQ_{it} = \beta X_{it} + \theta\sum_{j=1}^{N} W_{ij} X_{jt} + \mu_i \tag{15}$$

$$\mu_i = \lambda W\mu + \varepsilon_i \tag{16}$$

When $\lambda = 0$, $\rho \neq 0$ and $\theta \neq 0$, equation 2.13 is transformed into a spatial Durbin model:

$$GGAQ_{it} = \beta X_{it} + \rho\sum_{j=1}^{N} W_{ij} GGAQ_{jt} + \theta\sum_{j=1}^{N} W_{ij} X_{jt} + \varepsilon_i \tag{17}$$

The three models are suitable for the analysis of the influencing factors of different mathematical fractals, and the most suitable influencing factor regression model for this study can be determined only after the correlation coefficient test.

5 Empirical findings

5.1 Provincial change characteristics

Fig. 3 shows the distribution of the green production index, green life index, green ecological index, innovation input index, innovation performance index and innovation potential index, which are components of the green development index and innovation-driven development index, in 11 provinces and cities along the Yangtze River Economic Belt in 2003, 2010 and 2017. The green production index, green living index and innovation performance index show a trend of balanced development, and the gap between the 11 provinces and cities gradually narrows over time. The green ecological index, innovation input index and innovation potential index presents little change, and the spatial distribution characteristics presented a stable and unbalanced distribution.

Fig. 4 shows that the 11 provinces and cities in the Yangtze River Economic Belt have great differences in their innovation-driven indexes, and the spatial pattern is relatively stable over time. The differences in the green development index and comprehensive development index between provinces and cities gradually narrow over time, presenting a more balanced distribution trend.

The coupling relationship and coordination relationship between the innovation-driven index and green development index in 11 provinces and cities along the Yangtze River Economic Belt have a high matching degree (Fig. 5); they are all at a high level, and the differences between provinces and cities are small.

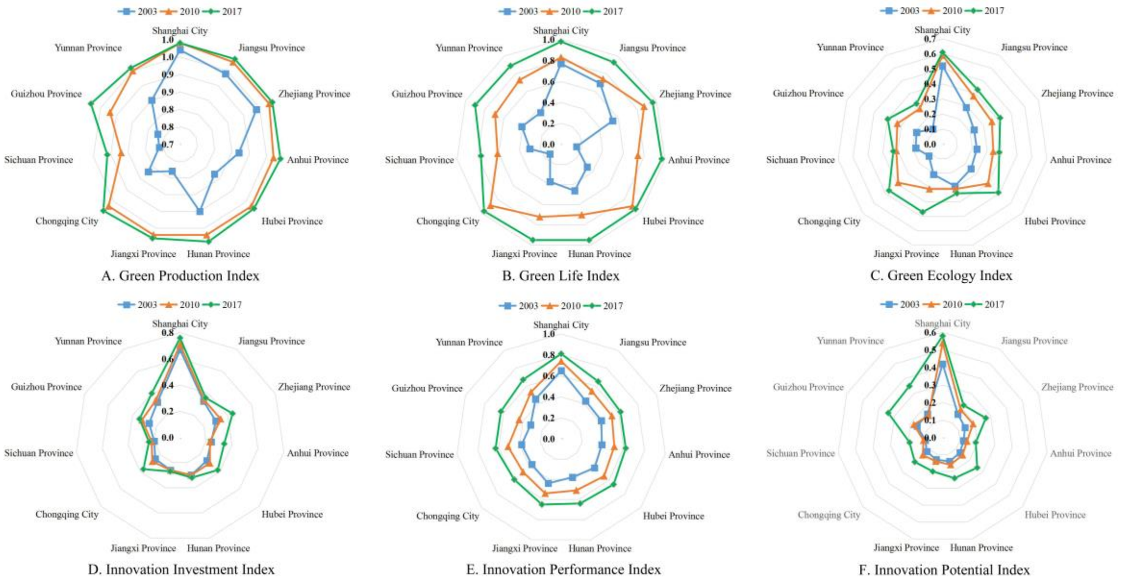

Fig. 3 The distribution of the green production index, green life index, green ecology index, innovation input index, innovation performance index and innovation potential index in 11 provinces and cities of the Yangtze River Economic Belt in 2003, 2010 and 2017

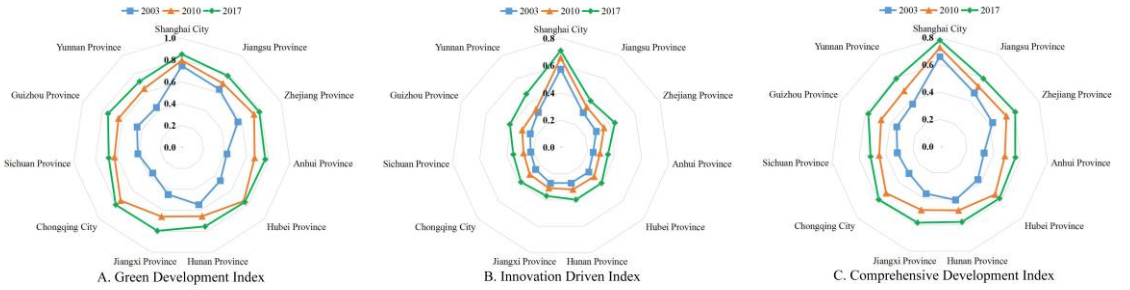

Fig. 4 The distribution of the innovation-driven index, green development index and comprehensive development index of 11 provinces and cities in the Yangtze River Economic Belt in 2003, 2010 and 2017

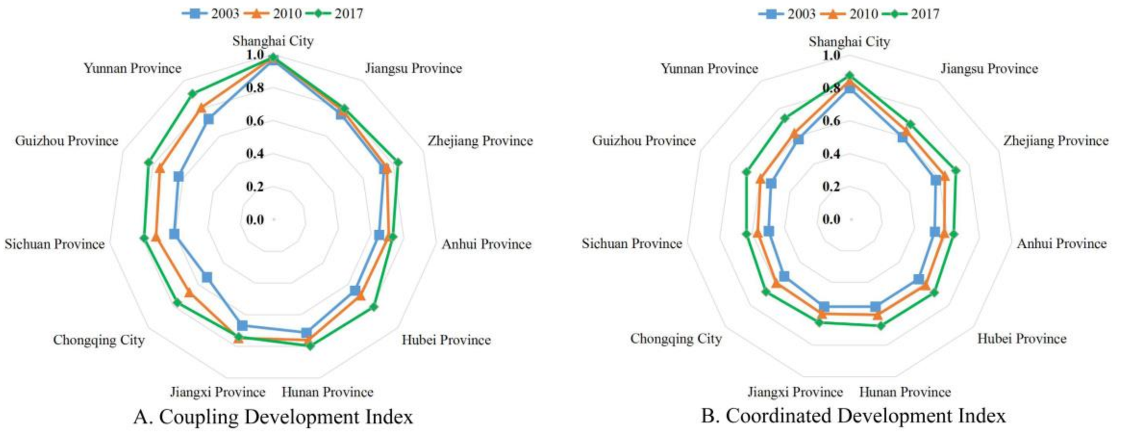

Fig. 5 Coupling coordination index distribution of green development and innovation drive in 11 provinces and cities along the Yangtze River Economic Belt in 2003, 2010 and 2017

5.2 Urban change characteristics

Cities with a high index value tend to form high-value planar areas, while cities with a low index tend to form low-value agglomeration areas. As shown in Figure 6, the spatial distribution of the innovation-driven index of 130 cities in the Yangtze River Economic Belt in 2003, 2010 and 2017 show significant differences. The high-value areas of the innovation-driven index are distributed in a point-like form, and the low value area gradually expands.

Compared with the innovation-driven index, the green development index in the Yangtze River Economic Belt has a strong high-value agglomeration feature in terms the temporal and spatial distribution. As shown in Figure 7, the high-value area of the green development index gradually expands from east to west, while the low-value area gradually shrinks.

Figure 8 shows the spatial distribution characteristics of the coordination index of innovation-driven development and green development. The high values of the coordination index are distributed in central cities, such as provincial capitals, while the low-value areas show an overall expanding trend.

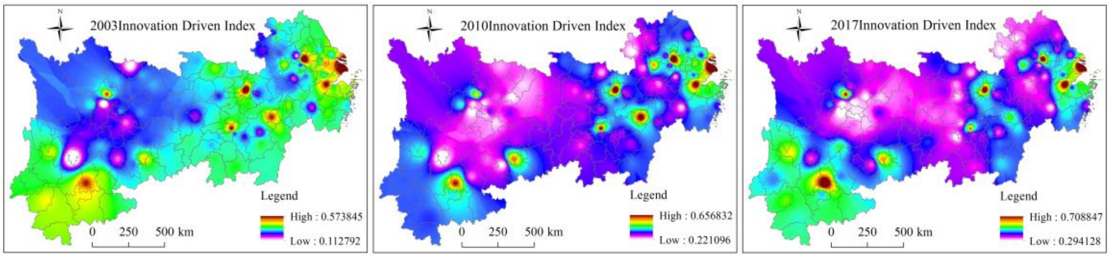

Fig. 6 Spatial distribution of the innovation-driven indexes of 130 cities in the Yangtze River Economic Belt in 2003, 2010 and 2017

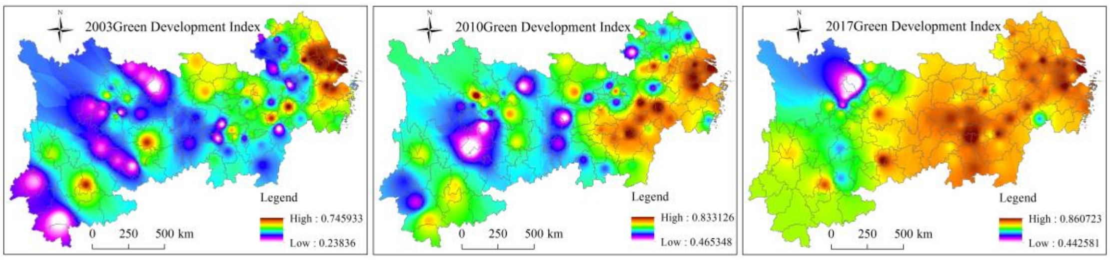

Fig. 7 Spatial distribution of the green development indexes of 130 cities in the Yangtze River Economic Belt in 2003, 2010 and 2017

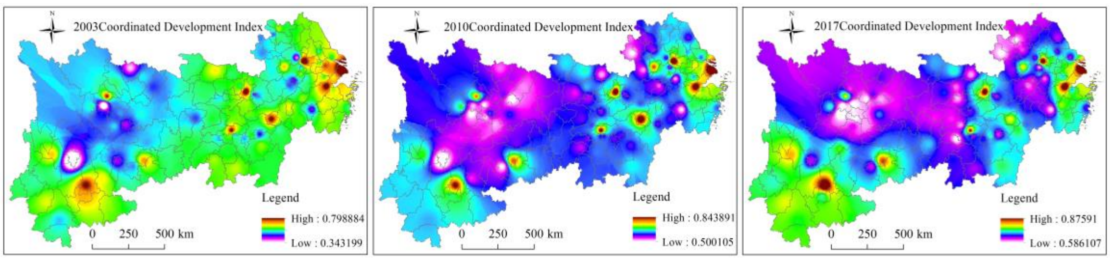

Fig. 8 Spatial distribution of the innovation-driven development and green development coordination indexes of 130 cities in the Yangtze River Economic Belt in 2003, 2010 and 2017

5.3 Spatial heterogeneity analysis

To solve the problem of regional integration development and balanced distribution, it is important to use spatial heterogeneity analysis as a tool to determine the abnormal value of spatial distribution. As shown in Table 2, the global autocorrelation indexes of the innovation-driven development index, green development index and coordinated development index of the Yangtze River Economic Belt in 2003, 2010 and 2017 are all positive, indicating that these indexes have positive clustering characteristics in terms of their spatial distribution, and all pass the significance test at the 5% level, indicating that the results of spatial heterogeneity analysis are credible.

As shown in Figure 9, the clusters with a high innovation-driven development index are distributed in the eastern cities. The low-high cluster city is Chuzhou, compared with nearby Nanjing. The high-low clusters include Wuhan, the capital city of Hubei Province, and Chengdu, the capital city of Sichuan Province. The surrounding areas of the low-low clusters are all nonsignificant areas, which are evenly distributed in the central and western regions of the Yangtze River Economic Belt.

The spatial heterogeneity distribution of the green development index is similar to that of innovation-driven development. As shown in Figure 10, many high-high clusters are distributed around Shanghai. Only Chengdu, Sichuan Province, remains in the high-low cluster. The low-low clusters are still distributed in the middle and western regions of the Yangtze River Economic Belt.

The spatial distribution characteristics of the coordinated development index are significantly different from those of the green development index and innovation-driven development index, and the outliers are mostly distributed in point-shaped form (Figure 11). The high-high cluster is still dominated by Shanghai and its surrounding areas. The high-low clusters are the provincial capitals of the central and western provinces of the Yangtze River Economic Belt, and the low-low clusters are distributed around them. The low-high clusters are distributed around the high-high clusters.

Table 2 Global autocorrelation test

	I Index	Expectation Index	Variance	Z Score	P Value
2003 Green Development Index	0.4531	-0.0093	0.0042	7.1589	0.0000
2010 Green Development Index	0.2649	-0.0093	0.0042	4.2541	0.0000
2017 Green Development Index	0.5616	-0.0093	0.0038	9.2172	0.0000
2003 Innovation-Driven Development Index	0.0839	-0.0093	0.0039	1.8912	0.0359

2010 Innovation-Driven Development Index	0.1379	-0.0093	0.0039	2.3649	0.0179
2017 Innovation-Driven Development Index	0.1381	-0.0093	0.0041	2.3342	0.0196
2003 Coordinated Development Index	0.1147	-0.0093	0.0039	1.9572	0.0503
2010 Coordinated Development Index	0.1782	-0.0093	0.0039	2.9595	0.0031
2017 Coordinated Development Index	0.2176	-0.0093	0.0041	3.5596	0.0000

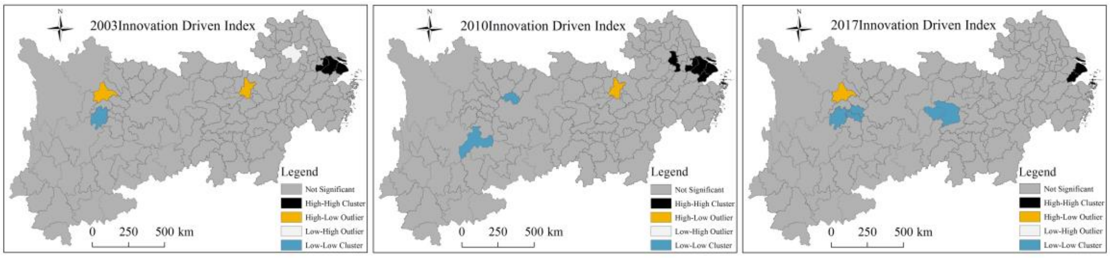

Fig. 9 LISA distribution of the innovation drive indexes of 130 cities in the Yangtze River Economic Belt in 2003, 2010 and 2017

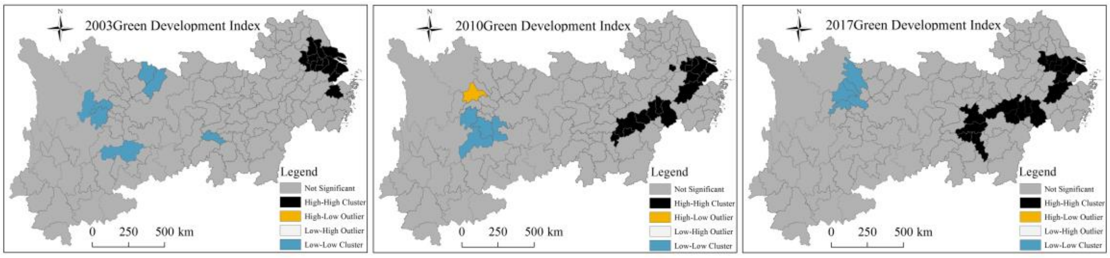

Fig. 10 LISA distribution of the green development indexes of 130 cities in the Yangtze River Economic Belt in 2003, 2010 and 2017

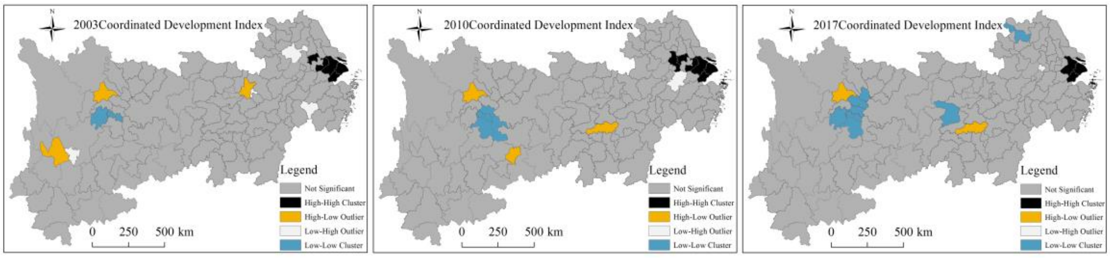

Fig. 11 LISA distribution of the innovation-driven development and green development coordination indexes of 130 cities in the Yangtze River Economic Belt in 2003, 2010 and 2017

5.4 Influencing mechanism analysis

The above analysis shows that the coupling index and the coordination index of innovation-driven development and green development of the Yangtze River Economic Belt have the characteristics of spatial heterogeneity, indicating that different characteristic variables have different influences on the two, and their influence presents spatial variation. Therefore, the spatial panel regression model is used to discuss the interaction between the structure of innovation-driven development and green development in the Yangtze River Economic Belt. Table 4-5 show that the SDM has a higher R^2 than the SLM and SEM and that the SDM passes the Hausman test at the

1% confidence level and rejects the random effect. Therefore, we focus only on the regression results of the fixed-effect SDM in Tables 3-4.

5.4.1 The innovation-driven impact on green development

The results in Table 3 show that the proportion of R&D investment in GDP (KB), the number of R&D personnel per ten thousand people (KR), the education expenditure per ten thousand yuan of GDP (JZ) and the number of education practitioners per ten thousand people (EP) all have a significant positive impact on the regional green development index. The two indicators, the proportion of R&D investment in GDP and the number of R&D personnel per ten thousand people, have an intermediary effect on the region but no significant effect on the green development of neighbouring areas. Education expenditure per ten thousand GDP and the number of educated employees per ten thousand GDP have not only a positive effect on the level of green development in this region but also a positive correlation with neighbouring regions.

5.4.2 Green development feeds back into innovation-driven development

Table 4 shows that there is a significant interaction between the innovation drive development index and the gross value of industrial wastewater emissions per ten thousand yuan of industrial output (FS), the hazard-free treatment rate of waste (WL), days with good air quality (YK) and the ratio of surface water at or better than class III (GP). The two indicators of wastewater emissions per ten thousand yuan of industrial output and the hazard-free treatment rate of waste have direct effects only on the regional innovation drive development index, with high correlation coefficients. Wastewater emissions per ten thousand yuan of industrial output is negatively related with the regional innovation drive development index and the hazard-free treatment rate of domestic waste is positively. There is a significant positive correlation between the two indicators of the proportion of days with good air quality in the whole year and the proportion of surface water at least or better than type III and the innovation drive development index of the region and adjacent regions.

Table 3 Panel model regression results of green development impact factors

Effect	Variable	SLM-FE Coefficient value	P value	SLM-RE Coefficient value	P value	SEM-FE Coefficient value	P value	SEM-RE Coefficient value	P value	SDM-FE Coefficient value	P value	SDM-RE Coefficient value	P value
Direct effect	lnKZ	0.177***	0.000	0.170***	0.000	0.205***	0.00	0.198***	0.000	0.074***	0.000	0.069***	0.000
	lnKB	0.061	0.122	0.038	0.204	0.031	0.41	0.076***	0.005	0.232***	0.001	0.022	0.636
	lnKR	0.191***	0.000	0.182***	0.000	0.075***	0.00	0.068***	0.000	0.283***	0.000	0.076***	0.000
	lnZS	0.083**	0.020	0.074***	0.007	0.064*	0.05	0.073***	0.004	0.062*	0.055	0.059**	0.046
	lnNH	-0.105**	0.003	-0.103***	0.004	-0.134***	0.00	-0.125***	0.000	-0.107***	0.000	-0.106***	0.001

Effect	Variable	SLM-FE Coefficient value	P value	SLM-RE Coefficient value	P value	SEM-FE Coefficient value	P value	SEM-RE Coefficient value	P value	SDM-FE Coefficient value	P value	SDM-RE Coefficient value	P value
	lnZD	0.082***	0.000	0.083***	0.000	0.112***	0.00	0.107***	0.000	0.051***	0.000	0.059***	0.000
	lnJZ	0.383***	0.000	0.382***	0.000	0.307***	0.00	0.304***	0.000	0.308***	0.001	0.298***	0.000
	lnCS	0.038	0.315	0.008	0.827	0.064*	0.097	0.048	0.179	0.034	0.312	0.013	0.717
	lnEP	0.247**	0.014	0.256***	0.006	0.042**	0.028	0.054***	0.005	0.269***	0.000	0.275***	0.000
Indirect effect	lnKZ	0.020***	0.001	0.014***	0.005					0.058	0.217	0.034	0.542
	lnKB	0.008	0.201	0.003	0.277					0.029	0.798	0.003	0.977
	lnKR	0.010**	0.004	0.007**	0.017					0.029	0.164	0.035*	0.054
	lnZS	0.010*	0.080	0.006*	0.065					0.037	0.607	0.015	0.833
	lnNH	-0.011**	0.006	-0.008**	0.015					-0.152***	0.000	-0.196***	0.000
	lnZD	0.037**	0.002	0.027**	0.011					0.026	0.586	0.009	0.862
	lnJZ	0.009***	0.000	0.007***	0.004					0.120***	0.000	0.207***	0.000
	lnCS	0.004	0.375	0.001	0.928					0.105	0.185	0.097	0.263
	lnEP	0.005*	0.062	0.005*	0.075					0.153***	0.000	0.133***	0.001
Total effect	lnKZ	0.197***	0.000	0.184***	0.000					0.233***	0.000	0.203***	0.001
	lnKB	0.069	0.127	0.040	0.204					0.161	0.207	0.019	0.883
	lnKR	0.101***	0.000	0.089***	0.000					0.112***	0.000	0.111***	0.000
	lnZS	0.092**	0.022	0.081***	0.007					0.025	0.773	0.074	0.374
	lnNH	-0.116**	0.002	-0.112***	0.002					-0.459***	0.000	-0.402***	0.000
	lnZD	0.365***	0.000	0.335***	0.000					0.281***	0.000	0.289***	0.000
	lnJZ	0.092***	0.000	0.089***	0.000					0.071***	0.001	0.066***	0.006
	lnCS	0.042	0.317	0.009	0.834					0.139	0.124	0.110	0.273
	lnEP	0.053**	0.015	0.061***	0.007					0.083**	0.062	0.058	0.210
R^2	within	0.987		0.986		0.986		0.986		0.990		0.989	
	between	0.952		0.975		0.972		0.973		0.976		0.936	
	overall	0.944		0.977		0.969		0.976		0.984		0.946	
Mean of fixed-effects		0.047				0.052				0.120			
Hausman		6.770***				10.700***				19.280***			
Log-Likelihood		615.129		580.751		612.666		580.612		638.832		598.403	

Note: *, **, *** indicate the significance level of 10%, 5%, and 1%.

Table 4 Panel model regression results of innovation-driven development impact factors

Effect	Variable	SLM-FE Coefficient value	P value	SLM-RE Coefficient value	P value	SEM-FE Coefficient value	P value	SEM-RE Coefficient value	P value	SDM-FE Coefficient value	P value	SDM-RE Coefficient value	P value
Direct effect	lnFS	-0.146***	0.001	-1.042***	0.003	-0.133**	0.011	-0.130**	0.025	-0.149***	0.001	-0.145***	0.002
	lnFL	-0.020	0.242	-0.015	0.418	-0.011	0.568	-0.005	0.817	-0.019	0.340	-0.013	0.543
	lnFF	-0.085***	0.000	-0.091***	0.000	-0.097***	0.000	-0.103***	0.000	-0.071***	0.000	-0.079***	0.000
	lnWS	0.040***	0.000	0.038***	0.000	0.046***	0.000	0.043***	0.000	0.030***	0.000	0.030***	0.000
	lnWR	0.024***	0.010	0.025***	0.008	0.039***	0.000	0.039***	0.000	0.016***	0.005	0.017***	0.008
	lnWL	0.192***	0.000	0.185***	0.000	0.155***	0.000	0.152***	0.001	0.133***	0.000	0.125***	0.000
	lnPG	0.011	0.421	0.010	0.457	0.010	0.454	0.010	0.477	0.016	0.325	0.015	0.370
	lnYK	0.180*	0.092	0.195**	0.050	0.086	0.116	0.105*	0.064	0.180***	0.006	0.199***	0.001
	lnGP	0.159***	0.000	0.161***	0.000	0.174***	0.000	0.174***	0.000	0.147***	0.001	0.148***	0.001
Indirect effect	lnFS	0.019**	0.037	0.015*	0.062					-0.014	0.708	-0.006	0.890
	lnFL	0.008	0.311	0.005	0.466					0.040	0.505	0.039	0.513

	lnFF	-0.034***	0.002	-0.032***	0.007					-0.039	0.250	-0.031	0.318
	lnWS	0.056***	0.002	0.049***	0.006					0.051	0.160	0.053	0.119
	lnWR	0.009***	0.008	0.008**	0.015					0.061***	0.001	0.056***	0.004
	lnWL	0.037**	0.013	0.031**	0.030					0.040	0.471	0.036	0.523
	lnPG	0.004	0.483	0.004	0.530					0.015	0.734	0.004	0.930
	lnYK	0.133***	0.009	0.135***	0.004					0.103***	0.006	0.118***	0.004
	lnGP	0.123***	0.001	0.121***	0.004					0.131***	0.001	0.123***	0.002
Total effect	lnFS	0.164***	0.003	0.158***	0.006					0.035	0.425	0.040	0.391
	lnFL	0.029	0.254	0.020	0.424					0.059	0.417	0.051	0.478
	lnFF	-0.019***	0.000	-0.022***	0.000					-0.010***	0.001	-0.010***	0.000
	lnWS	0.096***	0.000	0.087***	0.000					0.081***	0.000	0.082***	0.000
	lnWR	0.033***	0.005	0.033***	0.004					0.067***	0.002	0.063***	0.010
	lnWL	0.129***	0.000	0.117***	0.000					0.172**	0.016	0.161**	0.031
	lnPG	0.015	0.434	0.014	0.471					0.031	0.543	0.019	0.701
	lnYK	0.113***	0.008	0.130***	0.002					0.183***	0.003	0.128***	0.005
	lnGP	0.182***	0.000	0.162***	0.000					0.117***	0.001	0.171***	0.005
R^2	within	0.898		0.898		0.892		0.891		0.907		0.907	
	between	0.001		0.078		0.318		0.483		0.703		0.001	
	overall	0.031		0.086		0.200		0.303		0.401		0.029	
Mean of fixed-effects		0.144				0.189				0.194			
Hausman		3.590***				3.580***				4.890***			
Log-Likelihood		578.311		527.116		571.853		522.735		585.189		533.424	

Note: *, **, *** indicate the significance level of 10%, 5%, and 1%.

6 Discussion

6.1 The spatial distribution of the innovation-driven development and green development coordination indexes

This study shows that the spatial distribution of the innovation-driven development and green development coordination indexes in the Yangtze River Economic Belt presents an unbalanced trend and that the differences between cities and regions are gradually increasing, especially between central cities (provincial capitals, municipalities directly under the central government, etc.) and surrounding cities. An increase or decrease in the coordination index reflects an increase or decrease in the cooperation coefficient between innovation-driven development and green development. From the perspective of classification, from 2003 to 2017, the high-value area of the green development index of the Yangtze River Economic Belt shows an expanding trend from the east to the centre, while the high-value area of the innovation-driven development index shows a shrinking trend from the centre to the east. Such spatial distribution characteristics are related to the administrative system with Chinese characteristics. Innovation depends on the investment of science and education funds and personnel. Compared with central cities, general cities in the western region have limited science and education resources, which cannot be closely connected with innovation-driven development. The lack of coordination between the two leads to the lack of sustainability and self-generation of regional green development. Therefore, finding the innovation-driven green development path of the general cities of the Yangtze River Economic Belt is a feasible way to support the region’s green and sustainable development.

6.2 Spatial heterogeneity of the innovation-driven development and green development coordination index

Spatial heterogeneity across regions is a key issue for the coordination between the innovation-driven development and green development of the Yangtze River Economic Belt. According to the above research conclusions, there is significant spatial heterogeneity across regions of the Yangtze River Economic Belt in terms of the innovation drive development index, green development index and coordinated development index from 2003 to 2017. Low-low clusters indicate that the development index values of a region and its surrounding regions are significantly low; such areas are mainly distributed in the central and western regions of the Yangtze River Economic Belt. Compared with the downstream areas, these areas have a low economic development level, a poor innovation atmosphere, and limited green development and therefore form an agglomeration area with low-low clusters. High-high clusters refer to the areas with high development indexes of their own and in the surrounding areas within the Yangtze River Economic Belt. Such areas are concentrated in the eastern region with a high level of economic development, high investment in innovation resources and an interactive and cooperative mechanism between innovation and green development. The coordination index of low-high clusters is significantly lower than that of surrounding areas. Policy mechanisms, such as resource investment, process management and efficiency improvement, should be developed to quickly improve the unfavourable positions of these areas and facilitate the spatial expansion and extension of high-value areas. The coordination index of high-low clusters is significantly higher than that of the surrounding areas. How to link related resources and drive the coordinated development of surrounding areas is the core of improving the overall level of low-low clusters.

6.3 Interaction mechanism between innovation-driven development and green development

The analysis of the impact mechanism is a key step in promoting innovation-driven development and green development. In the interaction between innovation-driven development and green development in the Yangtze River Economic Belt, there are many-to-one and one-to-many relationships between the two impact modes. To improve the level of green development in low-high clusters, it is necessary to increase the proportion of R&D investment in GDP and increase the number of R&D personnel per ten thousand people, as both of these indicators have a significant positive impact on the improvement in the level of green development in the region. To improve the green development level of low-low clusters, it is necessary to increase the education expenditure per ten thousand GDP and increase the number of education employees per ten thousand people. Both of these measures not only improve the green development level of their own region but also have a significant impact on the green development level of neighbouring regions, and they are thus suitable for contiguous low-low clusters.

The influencing mechanism of the innovation-driven development index is also improved by differentiation according to the sub-regional types mentioned above. For continuous innovation in the low index areas of low-low clusters, the application of two-way indicators has direct effects and indirect effects, enhancing the overall level of innovation in these clusters. The model results show that indexes such as the proportion of days with good air quality and the ratio of surface water at or better than level III can be effectively improved. For the development of low-high clusters, the indexes with significant effects in individual regions but not neighbouring regions should be selected. The model results highlight the importance of the two indexes of industrial wastewater discharge per ten thousand yuan of industrial output value and the harmless disposal rate of domestic waste. Reducing the industrial wastewater discharge per ten thousand yuan of industrial output value and increasing the harmless treatment rate of domestic waste can effectively improve the innovation-driven development index of low-high clusters.

6.4 Strengths and limitations

This study has several advantages. First, the Yangtze River Economic Belt, a pilot area of innovation-driven development and green development in China, is taken as a case to study the coordinated relationship between innovation-driven development and green development. This study is representative and can be used as a reference for the development of other regions. Second, by constructing an evaluation index system, we evaluate the innovation-driven development index and green development index in different dimensions, which can comprehensively represent the actual level of evaluation targets. Third, by decomposing the overall and local relationships between innovation-driven development and green development, we can find specific indicators with spatial heterogeneity to support the implementation of countermeasures and suggestions.

Our study has some limitations. First, the study scale of spatial distribution is at the provincial level and the city level, and some characteristic conclusions are drawn. However, some indicators, such as the domestic sewage treatment rate, household garbage harmless treatment rate, and per capita park green area, can be refined to more microscopic research scales, such as the county level and township level, and more detailed research conclusions can be drawn to overcome the spatial limitations of this study. Second, the index data from the China Statistical Yearbook, such as per capita park green area, green coverage rate of built-up areas, science and technology expenditure per ten thousand GDP, and education expenditure per ten thousand GDP, are counted only in municipal districts, and the integrity of the research data needs to be further strengthened. Third, in the chapter on the influencing mechanism, we analyse the action mechanism of specific indicators on the overall development, including the differentiation analysis of both an individual region and adjacent regions. However, some indicators also have differences in the action cycle or even lag effects, which are not extended to the action cycle due to the model limitations. All the above three points need to be addressed in follow-up studies.

7 Conclusion

In this paper, the entropy weight TOPSIS method and the coupling coordination model were used to evaluate the coupling coordination relationship between innovation-driven development and green development in the Yangtze River Economic Belt, and the influencing mechanism between the two was explored from the perspective of spatial panel data. In general, the coordination index of innovation-driven development and green development in the 11 provinces and cities of the Yangtze River Economic Belt has a distribution pattern of high in the east and low in the west. The eastern coastal region of the Yangtze River Economic Belt, as the frontier for the land acquisition of foreign enterprises, presents strong coordination between innovation-driven development and green development. The improvement in innovation ability can support advancement toward the goal of green development, and green development can optimize the development environment and promote the further improvement in innovation ability. The central and western regions of the Yangtze River Economic Belt are located inland, and their innovation-driven development and green development indexes are both low, indicating that these regions have not formed a well-coordinated relationship. Local influencing factors have significantly heterogeneous effects on the overall development space. This study fills the gap in the literature regarding the interaction mechanism between innovation-driven development and green development in the academic world, and the proposed evaluation index system has a certain universality and significance.

Authors′ contribution

Wei Wang: Conceptualization, Methodology, Software and Writing.

Lei Zhou: Visualization, Investigation and Writing.

Wei Chen: Writing, Software, Validation.

Chao Wu: Writing, Reviewing and Editing.

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