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Original Research

The Influence of Coupling Degree of Technological Innovation and Industrial Structure Upgrading on the Green Economic Efficiency

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Abstract

Technological innovation and industrial structure upgrading have become two strategic initiatives to realize a green economic development in the new development model of China. Exploring the relationship between green economic efficiency and the coupling degree of technological innovation and industrial structure upgrading is essential to achieve the visionary goal of green economic development and socialist modernization. This paper measures the coupling degree of technological innovation and industrial structure upgrading, classifies the coupling types based on the panel data of 30 provinces in China from 2012-2019, and measures the green economic efficiency of 30 provinces in China using the super-efficient model (SBM), based on a spatial econometric model to study the relationship between green economic efficiency and the coupling degree of technological innovation and industrial structure upgrading. The research results show that there is a significant positive effect on green economic efficiency among regions; the coupling degree of technological innovation and industrial structure upgrading has a significant direct effect and a spatial spillover effect on green economic efficiency, the spatial spillover effect plays a major role. The heterogeneity analysis reveals that in the regions with higher development and coordination degrees of technological innovation and industrial structure upgrading, the coupling degree of technological innovation and industrial structure upgrading has a significant effect on the green economic efficiency of the region, and in the regions with lower development and coordination degrees of technological innovation and industrial structure upgrading, the coupling degree of technological innovation and industrial structure upgrading has a significant positive effect on the green economic efficiency of the region and neighboring areas.

Keywords: technological innovation, industrial structure upgrading, green economic efficiency, coupling degree, spatial econometric model

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Introduction

In recent years, the resource bottleneck and environmental constraints on global economic and social development have become increasingly tight, and resource and environmental issues have become a key factor affecting sustainable economic and social development. China is in a period of industrialization and urbanization, and the industrial-led industrial structure and the energy structure dominated by non-renewable resources will continue to exist for some time in the future. At present, the development of green economy has risen to a global consensus. The core of the development of green economy lies in improving green economic efficiency, which is a comprehensive economic efficiency based on economic efficiency with comprehensive consideration of resource input and environmental constraints. It is a measure of the level of green economic development. As people have a better quality of life and gradually increase their demand for green ecological environment, the green development concept of "green water and green hills are golden mountains" is deeply rooted in people's hearts, and the traditional sloppy development model with industry as the pillar industry is unsustainable, which means that China must shift from the factor-driven and investment scale-driven "sloppy growth" to the "intensive growth" that relies on technological innovation and industrial structure upgrading. The "innovation dividend" and "structural dividend" are considered to be the key windows to achieve green total factor productivity improvement under the new economic normal [1]. Thus, it can be seen that how to promote green economic efficiency through the coordinated development of technological innovation and industrial structure upgrading has become a hot issue to be urgently addressed.

According to the new economic growth theory, technological innovation is the core element to promoting economic growth, and the role of science and technology to promote and lead the economy is increasingly prominent [2]. Technological innovation has become a core element in the competition for comprehensive national power in global economies and an important driving force for green economic development [3]. Technological transformation is the key to achieving sustainable development [4], and technological innovation plays a very important role in the development of a green economy [5], green scientific and technological innovation will affect ecological civilization from multiple aspects of the supply chain dimension [6]. Some scholars believe that the impact of scientific and technological innovation on resources and the environment is manifested in several aspects, and technological innovation helps the research and development of environmental protection products as well as energy-saving equipment, which can effectively reduce pollutant emissions, improve resource utilization efficiency, and enhance environmental governance [7]. The improvement of the level of technological innovation will promote the improvement of energy use efficiency in strategic emerging industries [8]. In real society, a very important indicator affecting the development of a regional green economy is carbon dioxide emissions, and the improvement of the level of technological innovation is conducive to the reduction of regional carbon dioxide emissions [9]. It can be seen that, on the one hand, technological innovation can improve the resource-carrying capacity, effectively alleviate the pressure of insufficient resources in the process of economic development by improving the efficiency of resource utilization, developing potentially available resources, and reducing the loss of resources in the transportation process; on the other hand, technological innovation can improve the environmental carrying capacity, and technological innovation can reduce the intensity of pollutant emissions in production and life by developing clean production technology, pollution treatment technology, ecological restoration technology, and play a certain role in repairing the ecological environment damaged areas, providing a better living environment for economic development.

At the same time, the industrial structure upgrading provides a guarantee for green economic development. Since the traditional industries relied on in China's early economic development are mainly low-end industries with high energy consumption and high pollution, this has led to serious damage to regional resources consumption and environment, many industrial safety accidents, and the green development of the economy has been seriously challenged. A large number of scholars have researched the relationship between industrial structure upgrading and green economic development, and most of them believe that the level of industrial structure upgrading will have a positive impact on the development of the regional green economy. Industrial restructuring plays a positive role in promoting the development of the green economy [10–12], which is conducive to reducing the emission of pollutants [13, 14] and can promote energy efficiency and green total factor productivity [15, 16].

In addition, technological innovation and industrial structure upgrading are not two independent systems, but there is a mutual interaction between them, and the synergy between technological innovation and industrial upgrading can play a positive role in economic growth [17], on the one hand, technological progress will greatly improve the efficiency of labor and capital, promote the deepening of the social division of labor and the reallocation of social resources and thus promote the optimization and upgrading of industrial structure [18, 19], technological innovation makes the industry renewed by creating new products of the industry, and promotes the optimization and upgrading of the industry and thus the greening of the economy [20]. On the other hand, the adjustment of industrial structure will bring demand for new technologies, new techniques, new methods, etc., and the generation of these demands will further pull technological innovation, providing more opportunities and more space for technological innovation [21, 22].

Through combing through the relevant literature, it can be seen that the existing studies have the following three limitations: (1) the existing literature mainly studies the influencing factors on economic growth, but there is little research on the main factors driving the development of a green economy in China in the context of the "new normal"; (2) existing studies mainly focus on the relationship between the two, with little literature examining the impact of technological innovation and industrial structure upgrading on green economic development; (3) the existing literature mainly studies the impact of technological innovation and industrial structure upgrading on green economy development from the perspective of development level, and there is little literature on the impact of technological innovation and industrial structure upgrading on green economy development in China from the perspective of both development degree and coordination degree. Based on this, this paper summarizes existing research findings and builds a spatial econometric model from the perspective of combining development and coordination degrees, using panel data from 30 Chinese provinces from 2012 to 2019 to conduct an empirical analysis to study the impact of the coupling degree of technological innovation and industrial structure upgrading on green economy efficiency. The purpose is to grasp the influence of technological innovation and industrial structure upgrading on the development of China's green economy and provide theoretical support for the realization of green economic development.

Methodology and Data

Model Construction

Coupling Model

At present, scholars mainly adopt two methods to measure the coupling degree between systems. The traditional coupling degree measurement method does not distinguish between coordination degree and coupling degree, and later scholars extended the coupling degree measurement model to measure the coupling degree between systems from two aspects: development degree and coordination degree. This paper will adopt the extended model to measure the coupling degree of technological innovation and industrial structure upgrading, and the specific measurement methods are as follows.

(1) Development degree model. A large number of existing scholars use the form of a linear function to construct the development model, but this model lacks certain rationality. Therefore, this paper adopts the model construction method of Lu et al. [23], assuming that the development degree model follows the form of the Cobb-Douglas function, and the model assumptions are as follows:

$$T = \lambda(X)^{\alpha}(Y)^{1-\alpha} \quad (1)$$

In the formula: X is the measured level of technological innovation; Y is the measured level of industrial structure upgrading; α, 1-α reflects the importance degree of technological innovation and industrial structure upgrading in the total system, this paper considers that technological innovation and industrial structure upgrading are equally important, α takes 0.5; λ is the exogenous quantity. As can be seen in Fig. 1, the X-axis indicates the level of technological innovation, the Y-axis indicates the level of industrial structure upgrading, and the T_1 and T_2 curves indicate the development level line of technological innovation and industrial structure upgrading. When the coordinate point falls on the development level line farther from the origin, it represents the higher development degree of technological innovation and industrial structure upgrading in the region. For example, the development degree of the point falling on the T_1 curve is higher than that of the point falling on the T_2 curve.

(2) Coordination degree model. The coupling contains not only the development degree of the system but also the coordination degree of the system. This paper draws on the research results of Liao et al. [24], and uses the deviation coefficient to measure the coordination degree of the system, and transforms the formula of the deviation coefficient into.

$$C_v = \sqrt{2(1-C)} \quad (2)$$

$$C = \left[\frac{4XY}{(X+Y)^2}\right]^2 \quad (3)$$

As shown in Fig. 2, when C = 1, the coordination level is the highest and the coordinate point falls

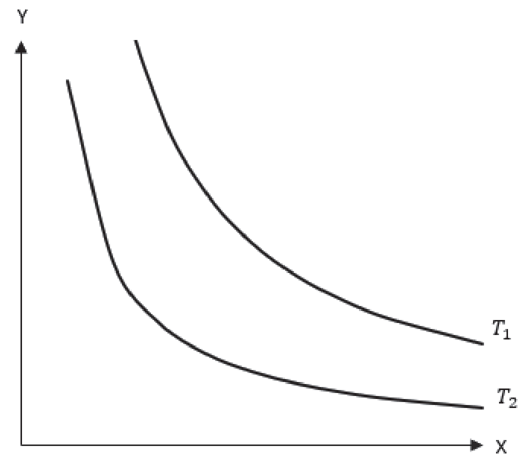

Fig. 1. Development degree analysis chart.

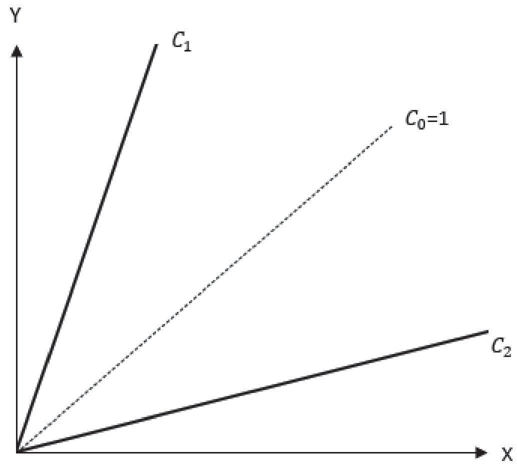

Fig. 2 Coordination analysis chart.

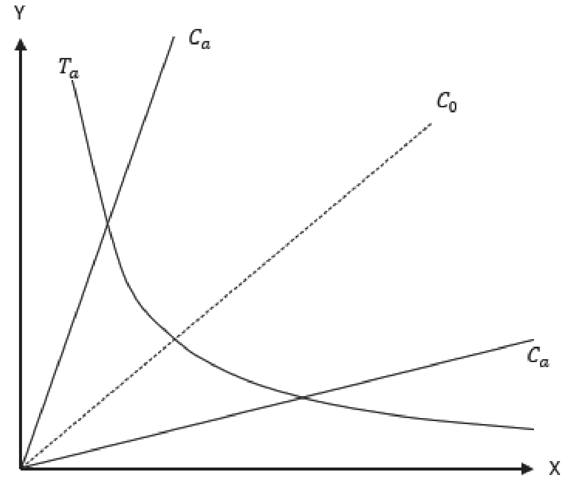

Fig. 3. Coupling degree analysis diagram.

on the straight line C_0 from the origin. With the change of coordination level in different regions, the coordinate point will fall on the straight line greater than 45° and less than 45°, and the closer to the straight line C_0, the higher coordination level. For example, when the coordinate points fall on the same straight line or a line symmetrical about C_0, it indicates that the coordination level of technological innovation and industrial structure upgrading in the two regions is the same. For example, the straight lines C_1 and C_2 in Fig. 2 are symmetrical about the straight line C_0, which means the coordination level of technological innovation and industrial structure upgrading at the points falling on the straight lines C_1 and C_2 is the same.

(3) Coupling model. The coordination degree measures the deviation of technological innovation and industrial structure upgrading levels, and the development degree measures the development level. The coupling degree between two systems of technological innovation and industrial structure upgrading needs to examine the development degree and coordination degree of the two systems at the same time. Therefore, the coupling degree formula is as follows:

$$D = \sqrt{C \times T} \tag{4}$$

According to the development degree and coordination degree of technological innovation and industrial structure upgrading, the level of coupling between technological innovation and industrial structure upgrading can be evaluated, and the coupling type of each region can also be classified. As shown in Figure 3, the curve T_α is the average development level line of all regions, the interval from the coordinate axis to the curve T_α is defined as the low development degree - coupling area, and the rest is defined as the high development degree - coupling area; the line C_α is the average coordination level line of all regions, the interval from the line C_0 to C_α is defined as the high coordination degree - coupling area, and the rest is defined as the low coordination degree - coupling area.

Spatial Econometric Model

In real society, the economic activities of different regions are not developed independently, and there are certain interactive relationships between them. Therefore, this paper adopts a spatial econometric model to study the relationship between green economic efficiency and coupling degree of technological innovation and industrial structure upgrading. The existing spatial econometric models mainly include three types: spatial error model (SEM), spatial lag model (SAR), and spatial Durbin model (SDM). The general expressions of the three types of spatial econometric models are as follows.

$$Y_{it} = \rho \sum_{j=1}^{n} W_{ij} Y_{jt} + \beta X_{it} + \gamma \sum_{j=1}^{n} W_{ij} X_{jt} + \mu_i + \xi_t + \delta_{it} \tag{5}$$

$$\delta_{it} = \lambda \sum_{i=1}^{n} W_{ij} \sigma_{jt} + \varepsilon_{it} \tag{6}$$

Where Y is the explained variable (green economic efficiency), Y_{it} is the green economic efficiency index of the i region in the year t; ρ refers to the spatial autocorrelation coefficient of green economic efficiency; X is the ensemble of explanatory variables, including the core explanatory variables of coupling degree of technological innovation and industrial structure upgrading and control variables, X_{it} is the explanatory variables of the i region in the year t; β, γ are the coefficients to be estimated; W_{ij} is the spatial weight matrix; μ_i is the spatial fixed effect, ξ_t is the time fixed effect, δ_{it} is the error term; λ is the spatial autocorrelation coefficient of the disturbance term. When ρ = γ = 0, it is the spatial error model; λ = γ = 0, it is the spatial lag model; λ = 0, it is the spatial Durbin model. In this paper, we introduce the geographic distance weight matrix and economic distance weight matrix to react to the influence of proximity on the explained variables. The specific formulas are as follow:

$$W_{1ij} = \begin{cases} 1/d_{ij}^{\ 2}, i \neq j \\ 0, i = j \end{cases} \quad (7)$$

$$W_{2ij} = \begin{cases} \dfrac{1}{\left|\bar{y}_i - \bar{y}_j\right|}, i \neq j \\ 0, i = j \end{cases} \quad (8)$$

Where i, j denote different regions, d_{ij} denotes the linear distance between region i and region j, and the weight of each region in the geographic distance weight matrix is expressed as the inverse of the 2nd power of distance; y_i, y_j denote the average GDP of region i and region j respectively, and the weight of each region in the economic distance weight matrix is expressed as the inverse of the absolute value of the difference of average GDP.

Variable Measurement

The Explained Variable

Green economic efficiency (GEE). A large number of scholars have used the DEA model to measure green economic efficiency, but this method is not applicable to the problem of efficiency evaluation that includes non-desired outputs. Therefore, this paper adopts the SBM model proposed by Tone [25], which provides an effective solution to the problem of non-desired outputs. In this paper, MaxDEA 8.21 software is used to measure the green economy efficiency values of 30 Chinese provinces from 2012 to 2019 using the super-efficient model (SBM), and the specific input indicators, expected output indicators, and non-expected output indicators are shown in Table 1.

Explanatory Variables

Coupling degree of technological innovation and industrial structure upgrading (D). Firstly, the evaluation indexes for technological innovation and industrial structure upgrading are constructed. In this paper, we mainly refer to the research of Zhang et al. [26] and Zhang et al. [27] to select the indexes from three aspects (technological innovation input, innovation output, and innovation environment) to measure the level of technological innovation. we refer to the research of Xu et al. [28] and Huo et al. [29] to select the evaluation indexes from two dimensions (industrial structure heightening and rationalization) to measure each region The entropy weight method was used to standardize the indicators and determine the weights of each indicator. The specific evaluation indexes are shown in Table 2.

After measuring the level of technological innovation and industrial structure upgrading in each region, the coupling degree model is constructed to measure the coupling degree of technological innovation and industrial structure upgrading. Fig. 4 shows the scatter plot of the average technological innovation level and the average industrial structure upgrading level of 30 provinces from 2012 to 2019, and the coupling types of each region are classified according to the average development level line T_α and the average coordination level line C_α of 30 provinces in Fig. 4, and the classification results are shown in Table 3.

Control Variables

In order to more objectively and accurately analyze the impact of scientific and technological innovation and industrial structure upgrading on green economic efficiency, other control variables are further selected to analyze the impact on green economic efficiency by combining theoretical analysis and referring to previous literature studies. Referring to the existing

Table 1 Green economic efficiency measurement indicators.

Type	Indicator	Specifics	Unit
Input Employed	Labor input	population in each region	Million people
	Capital investment	Fixed assets investment in each region	Billion yuan
	Energy input	Total energy consumption by region at the end of the year	Billion cubic meters
Expected output	GDP	GDP of each region at the end of the year	Billion yuan
Non-desired output	Waste water	Total chemical oxygen demand emissions	tons
		Total ammonia nitrogen emissions tons	tons
	Exhaust gas	Total sulfur dioxide emissions tons	tons
	Solid waste	Industrial solid waste generation	tons

Table 2 Technological Innovation and industrial structure upgrading indicators.

Subsystems	Tier 1 Indicators	Tier 2 Indicators	Unit	Weights
Technological Innovation	Innovation input	R&D investment intensity	%	0.0492
		R&D personnel full time equivalent	person	0.1361
		Ratio of education and science and technology expenditures to general budget expenditures	%	0.0041
	Innovation Output	Number of patents granted	term	0.1907
		Number of scientific and technical papers published in higher education institutions	piece	0.0715
		Technology Market Turnover	ten thousand yuan	0.2773
		Sales revenue of new products of industrial enterprises above the scale	ten thousand yuan	0.1884
	Innovation Environment	Average number of students enrolled in higher education per 100,000 population	person	0.0113
		GDP per capita	yuan	0.0273
		The proportion of industrial enterprises above the scale with R&D activities	%	0.0441
Industrial structure upgrading	Rationalization	Thiel index	/	0.2061
		The proportion of employment in the tertiary sector	%	0.0305
		Wastewater emissions of 10,000 Yuan GDP	Billion cubic meters / ten thousand yuan	0.3064
		Electricity consumption of 10,000 Yuan GDP	billion kilowatt hours / ten thousand yuan	0.1565
	Heightened	Servitization tendency	/	0.1078
		Social fixed asset investment to GDP ratio	%	0.0567
		Secondary industry labor productivity	%	0.0623
		Tertiary industry labor productivity	%	0.0737

theories and results [30, 31], the following control variables are selected in this paper: (1) openness to the outside world (OPEN) is measured by the ratio of total regional import and export trade to regional GDP; (2) government regulation (CON) is measured by the ratio of regional general local fiscal revenue to regional GDP. (3) Industrialization degree (IND): the total value of industrial output; (4) Urbanization level (URB): the ratio of the regional urban population to the total regional population is used to measure the urbanization level of the region.

Data Sources and Descriptive Statistics

Considering the problem of data acquisition and serious missing data in relevant studies in some regions, this paper selects data from 30 provinces and municipalities directly under the Central Government of China (except Hong Kong, Macao, Taiwan and Tibet) from 2012 to 2019 for the study. Individual missing data were supplemented by mean interpolation from the China Statistical Yearbook, provincial and municipal statistical yearbooks, the China Energy Statistical Yearbook, and the China Environmental Statistical

Table 3 Classification results of coupling types in 30 provinces.

	High development degree - coupling	Low development degree - coupling
High coordination -coupling	Beijing, Shanghai, Jiangsu, Zhejiang, Guangdong, Shandong, Hubei	Shaanxi, Anhui
Low coordination -coupling	Tianjin	Hebei, Shanxi, Inner Mongoria IM, Liaoning, Jilin, Heilongjiang, Fujian, Jiangxi, Henan, Hunan, Guangxi, Hainan, Chongqing, Sichuan, Guizhou, Yunnan, Gansu, Qinghai, Ningxia, Xinjiang

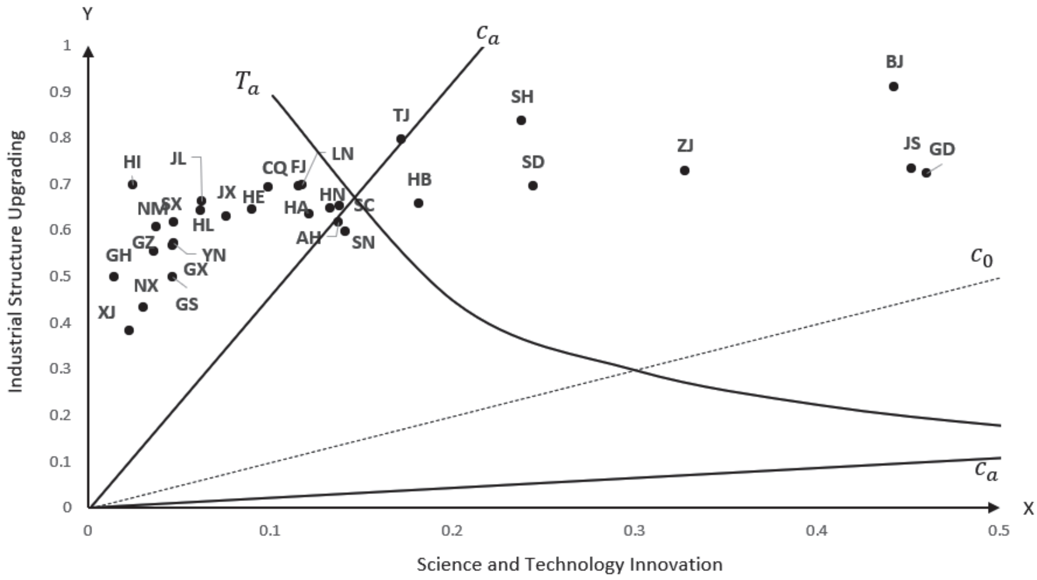

Fig. 4 Scatterplot of Technological Innovation and industrial structure upgrading level.

Table 4 Descriptive statistics of variables.

Variable Name	Symbol	Mean	Error	Standard	Min	Max
Green Economy Efficiency	GEE	240	0.645	0.113	0.307	0.987
Coupling degree of Technological Innovation and industrial structure upgrading	D	240	0.362	0.189	0.073	0.869
Degree of external openness	OPEN	240	4.104	4.545	0.182	22.830
Government Regulation	CON	240	11.290	3.110	6.893	22.730
Degree of industrialization	IND	240	0.953	0.816	0.048	3.939
Level of urbanization	URB	240	58.200	11.900	36.410	89.600

Yearbook. The basic information about the variables is shown in Table 4.

Results and Discussion

Spatial Correlation Analysis

Before the regression analysis of the spatial econometric model, the spatial correlation of green economic efficiency needs to be tested. The global Moran's I index is used to measure the spatial autocorrelation and significance of geographical objects in the study area on certain attributes. The formula is as follows.

$$I = \frac{n\sum_{i=1}^{n}\sum_{i=j}^{n} w_{ij}(x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1}^{n}\sum_{j\neq 1}^{n} w_{ij}\sum_{i=1}^{n}(x_i - \bar{x})^2} \quad (9)$$

In Equation (9), X_i, X_j denote the green economic efficiency of region i and region j, respectively, $\bar{X}$ denotes the average green economic efficiency of each region, and W_{ij} is the spatial weight matrix. Moran's I index takes values between [-1, 1], when Moran's I>0, it means positive spatial correlation, the large value the stronger positive spatial correlation; when Moran's I<0, it means negative spatial correlation, the smaller value the stronger negative spatial correlation; when Moran's I = 0, it indicates that there is no spatial autocorrelation in green economic efficiency.

As can be seen from Table 5, the global Moran's I index of green economic efficiency passed the 1% significance level test under the geographic distance spatial weight matrix and economic distance spatial weight matrix models from 2012 to 2019, with Moran's I>0, indicating that green economic efficiency in both Moran's I>0, indicating that green economic efficiency shows a spatially positive correlation distribution under both spatial weight matrices.

Selection of Spatial Panel Model

In order to make the research results more accurate and reliable, the models were tested before the spatial

Table 5. Moran's I values for green economic efficiency.

Year	W_1		W_2	
	Moran's I	Z	Moran's I	Z
2012	0.357***	4.173	0.658***	6.697
2013	0.358***	4.154	0.656***	6.635
2014	0.359***	4.178	0.647***	6.566
2015	0.352***	4.088	0.641***	6.492
2016	0.352***	4.076	0.627***	6.335
2017	0.319***	3.797	0.597***	6.168
2018	0.309***	3.648	0.597***	6.095
2019	0.214***	2.872	0.486***	5.107

econometric model analysis, and the relevant model test results are shown in Table 6. (1) LM test to determine the appropriate spatial econometric model, the test results significantly rejected the original hypothesis, indicating that this study should choose the spatial error model combined with the spatial lag model spatial Durbin model; (2) Hausman test results significantly rejected the original hypothesis, so the fixed-effect model was selected; (3) Through the LR test, Wald test can further verify the spatial Durbin model the fitness of the SDM model, and the test results all significantly reject the original hypothesis, indicating that the SDM model will not degenerate into the SAR and SEM models, further justifying the selection of the SDM model; (4) The spatial, temporal and Spatio-temporal fixed effects are tested and compared, and according to the test results, the Spatio-temporal fixed effects model is selected.

Spatial Durbin Model Regression Analysis

According to the test results, the spatial Durbin model with spatio-temporal fixed effects is selected for the empirical analysis in this paper, and the regression results in Table 7 show that the explanatory variables all pass the significance test. Under the two spatial weight matrix models, the spatial autoregressive coefficients ρ all passed the significance level test of 5%, indicating that under the influence of spatial interaction, the explanatory variable green economic efficiency has significant spatial dependence and green economic efficiency has a significant leading role among regions. The coupling degree of technological innovation and industrial structure upgrading passed the significance level test of 10% and the influence coefficient was positive, indicating that the improvement of the coupling degree of technological innovation and industrial structure upgrading plays a facilitating role in the improvement of green economic efficiency. The spatial interaction term of the coupling degree of technological innovation and industrial structure upgrading and the spatial weight matrix W_1 passed the significance test of 5%, and the spatial interaction term of the coupling degree of technological innovation and industrial structure upgrading and the spatial weight matrix W_2 passed the significance test of 10%, indicating that

Table 6. Correlation model test results.

Test type	Null hypothesis	Test result	
		W_1	W_2
LM_err	No spatial error effect	10.088***	5.043**
R-LM_err	No spatial error effect	4.310**	10.126***
LM_lag	No spatial lag	7.701***	13.115***
R-LM_lag	No spatial lag	5.721**	8.365***
Hausman-test	Random effect model	10.760*	161.830***
Wald (SAR)	SDM can be weakened to SAR	22.350***	10.110*
Wald (SEM)	SDM can be weakened to SAR	26.100***	11.770**
LR (SDM&SAR)	SDM can be weakened to SAR	21.560***	9.910*
LR (SDM&SEM)	SDM can be weakened to SAR	24.670***	11.450**

the coupling degree of technological innovation and industrial structure upgrading in the region also has a positive impact.

As for the control variables, the level of foreign openness passed the 10% significance level test, and the influence coefficient was greater than 0. This indicates that foreign openness is conducive to the improvement of green economic efficiency and that foreign openness can accelerate the flow of production factors such as capital between regions, promote the coordinated development of technological innovation and industrial structure, and improve green economic efficiency. Government regulation passed the significance level test of 1%, indicating that government regulation is conducive to the improvement of green economy efficiency because local governments attach great importance to the work related to green economic development, provide financial support and actively introduce relevant policies that can encourage enterprises to carry out green technological innovation and eventually help the green development of the economy. The degree of industrialization plays a significant inhibiting effect on the improvement of green economic efficiency. In the regions where the proportion of secondary industry is larger and industrial development is more prosperous, if the level of green technology cannot keep up with the rhythm of production, the more prosperous industrialization is, the greater the pressure on the environment and resources is, and industry, as the leading industry in China's national economy, promotes economic growth and at the same time generates greater pressure on resources and the environment. The level of urbanization passes the 1% significance level test, indicating that the increase in urbanization level will significantly contribute to the improvement of green economic efficiency. In the process of urbanization, people's awareness of environmental protection has increased, and the attitude toward nature-oriented life and the concept of low-carbon consumption are being practiced by more people. The improvement of urban quality of life, the follow-up of urban greening, and the centralized control of urban pollution all have positive effects on the green economy.

Table 7. Analysis of SDM regression results.

Variables	W_1	W_2
D	0.111* (0.059)	0.037* (0.086)
OPEN	0.010* (0.052)	0.012* (0.065)
CON	0.222*** (0.000)	0.220*** (0.000)
IND	-0.019* (0.069)	-0.008* (0.086)
URB	0.038*** (0.000)	0.034*** (0.000)
W*D	1.499** (0.020)	0.968* (0.088)
ρ	0.112** (0.031)	0.185** (0.010)
R^2	0.517	0.475
N	240	240

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

The total effect in the spatial Durbin model contains two parts, one is the direct effect on itself, and the other is the indirect effect (spatial spillover effect) produced by other regions. Based on this, this paper estimates the direct effect, spatial spillover effect, and total effect of the core explanatory variables of coupling degree of technological innovation and industrial structure upgrading on green economic efficiency, and the test results are shown in Table 8.

From the test results in Table 8, it can be seen that (1) Under the condition of geographic distance spatial weight matrix W1, the total effect coefficient of the coupling degree of technological innovation and industrial structure upgrading is 1.498, which indicates that for every 1% increase in the coupling degree of technological innovation and industrial structure upgrading, the overall green economic efficiency will rise by 1.498%; the direct effect of the coupling degree of technological innovation and industrial structure upgrading is 0.09, which indicates that the region The indirect effect of the coupling degree between technological innovation and industrial structure upgrading is 1.408, which indicates that for every 1% increase in the coupling degree between technological innovation and industrial structure upgrading, the green economic efficiency of the region with a close geographical distance will increase by 1.408%. (2) According to the direct effect results, a 1% increase in the degree of coupling of technological innovation and industrial structure upgrading in the region will result in a 0.067% increase in green economic efficiency. The indirect effect estimates show that for every 1% increase in the coupling degree of technological innovation and industrial structure upgrading in the region, the green economic efficiency of the region will increase by 0.816% in the areas close to the economic distance. It can be seen that the coupling degree of Technological Innovation and industrial structure upgrading will not only have a positive impact on the green economic efficiency of the region but also promote the improvement of green economic efficiency in areas with close geographical and economic distances. The spatial spillover effect is in the main position among the influence effects of technological innovation and industrial structure upgrading on green economic efficiency.

Heterogeneity Analysis

According to the different types of coupling, the heterogeneity analysis of the relationship between

Table 8. Analysis of the results of the direct and indirect effects of SDM.

Variables	W_1			W_2		
	Direct effect	Indirect effect	Total effect	Direct effect	Indirect effect	Total effect
D	0.090* (0.068)	1.408** (0.019)	1.498** (0.014)	0.067* (0.077)	0.816* (0.084)	0.883* (0.076)
OPEN	0.012* (0.053)	0.114** (0.041)	0.126** (0.024)	0.011* (0.054)	0.052** (0.017)	0.063** (0.014)
CON	0.214*** (0.000)	0.121** (0.037)	0.335*** (0.008)	0.214*** (0.000)	0.027* (0.086)	0.241** (0.014)
IND	-0.012 (0.280)	-0.253** (0.011)	-0.265** (0.023)	-0.003 (0.345)	-0.236** (0.027)	-0.239** (0.048)
URB	0.041*** (0.000)	-0.086*** (0.000)	-0.045** (0.048)	0.037*** (0.000)	-0.062*** (0.008)	-0.024** (0.029)

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

Table 9. Heterogeneity analysis test results.

Variables	High development degree - coupling		Low development degree - coupling	
	W_1	W_2	W_1	W_2
D	-0.232 (0.578)	-0.268 (0.879)	0.082*** (0.000)	0.066*** (0.000)
W*d	0.716*** (0.001)	0.173*** (0.002)	1.712** (0.026)	0.458** (0.047)
R^2	0.458	0.749	0.686	0.265
Variables	High coordination -coupling		Low coordination-coupling	
	W_1	W_2	W_1	W_2
D	-0.258 (0.206)	-0.203* (0.076)	0.198*** (0.005)	0.193* (0.073)
W*d	2.083*** (0.006)	1.754* (0.069)	0.755*** (0.000)	0.300*** (0.000)
R^2	0.269	0.875	0.314	0.258

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

green economic efficiency and the coupling degree of technological innovation and industrial structure upgrading was conducted, and the test results are shown in Table 9. The results of the study showed that (1) for high development-coupled regions, the influence of the coupling degree of technological innovation and industrial structure upgrading on the green economic efficiency of the region is not significant, but it has a significant promotion effect on the green economic efficiency in the neighboring regions. (2) For low development-coupled regions, the coupling degree of technological innovation and industrial structure upgrading passed the 1% significance test, and the coupling degree of technological innovation, industrial structure upgrading and the spatial interaction term of the spatial weight matrix passed the 5% significance test, indicating that the coupling degree of technological innovation and industrial structure upgrading has a significant positive impact on the green economic efficiency of both the region and the neighboring regions. (3) For the high coordination degree-coupled regions, the spatial interaction term of the coupling degree of technological innovation, industrial structure upgrading, and the spatial weight matrix passed the 1%, it shows that in high coordination-coupling regions, the increase of coupling between technological innovation and industrial structure upgrading significantly contributes to the improvement of green economic efficiency in neighboring regions. (4) For the low coordination-coupled areas, the coupling degree of technological innovation and industrial structure upgrading passed the significance level tests, and the coupling degree of technological innovation, industrial structure upgrading and spatial weight matrices passed the significance level tests, indicating that the coupling degree of technological innovation and industrial structure upgrading in the low coordination-coupling region has a positive effect on the green economic efficiency in the region and the nearby regions. To sum up, for the regions with a high development degree and a coordination degree of technological innovation and industrial structure upgrading, the regions should give full play to the spatial spillover effect of the coupling degree of technological innovation and industrial structure upgrading. For the regions with a low development degree and coordination degree of technological innovation and industrial structure upgrading, the regions should give full play to the direct effect of technological innovation and industrial structure upgrading coupling degree.

Conclusions and Policy Recommendations

Conclusions

Based on the summary of related studies, this paper measures the level of green economy efficiency, technological innovation, and industrial structure upgrading using the SBM model and the entropy value method for 30 Chinese provinces from 2012-2019. The coupling model is constructed from the perspective of development degree and coordination degree to measure the coupling degree between technological innovation and industrial structure upgrading and classify the coupling type. After that, we empirically study the influence of the coupling degree of technological innovation and industrial structure upgrading on green economic efficiency. By constructing a spatial econometric model, the direct effect and spatial spillover effect of the coupling degree of technological innovation and industrial structure upgrading on green economic efficiency are analyzed. In addition, the relationship between green economic efficiency and the coupling degree of technological innovation and industrial structure upgrading, is analyzed heterogeneously according to the different types of coupling. Based on the research, the main conclusions of this paper are as follows.

(1) The level of coupling between technological innovation and industrial structure upgrading shows an unbalanced development trend of "high in the east and low in the west". From the overall perspective, the coupling degree of technological innovation and industrial structure upgrading in most provinces shows a trend of the increasing year by year; by region, the average level of coupling degree of technological innovation and industrial structure upgrading in the eastern region is the highest, and the average level of coupling degree of technological innovation and industrial structure upgrading in the western region is the lowest. Most of the provinces in western China are at the lower development degree and lower coordination degree of technological innovation and industrial structure upgrading.

(2) There is a significant positive spatial correlation between the green economic efficiency of each region. That is, the green economic efficiency of the region is not only influenced by the degree of opening up, government regulation, industrialization, and urbanization of the region, but also influenced by the green economic efficiency of the neighboring regions, and this dependency is related to the geographical distance, and economic level.

(3) The improvement of coupling degree between technological innovation and industrial structure upgrading is conducive to the improvement of green economic efficiency. The direct effect, indirect effect, and total effect of the coupling degree of technological innovation and industrial structure upgrading on green economic efficiency are all significant positive effects. The coupling degree of technological innovation and industrial structure upgrading not only affects the green economic efficiency of the region, but also positively influences the green economic efficiency in the neighboring regions, and in comparison, the spatial spillover effect of the coupling degree of technological innovation and industrial structure upgrading on green economic efficiency plays a major role.

(4) According to the different types of coupling degree, the coupling degree of technological innovation and industrial structure upgrading has a heterogeneous influence on green economic efficiency. In regions with higher development and coordination degrees of technological innovation and industrial structure upgrading, the coupling degree of technological innovation and industrial structure upgrading has no significant influence on the green economic efficiency of the region and has a significant positive influence on the green economic efficiency of the neighboring regions; in regions with lower development and coordination degrees of technological innovation and industrial structure upgrading, the coupling degree of technological innovation and industrial structure upgrading has a significant positive influence on the green economic efficiency of the region and the neighboring regions.

Therefore, in order to give full play to the synergy between technological innovation and industrial structure upgrading, and to promote green economic development, this paper offers the following suggestions.

(1) Encourage positive interaction in a green economy by exchanging and learning from one another. Green economic efficiency has spatial mutual influence, so the government should pay attention to the development policies of neighboring regions in the process of formulating green economic development policies, and the regions with better green economic development should make use of their advantages to gather factors while strengthening exchanges and cooperation with regions with poor green economic development, to realize the benign interaction of green economic development.

(2) Encourage the development and focus on coordination. The government should play the role of

encouragement and support, increase policy support for technological innovation, encourage scientific research institutions, universities, and enterprises to carry out independent innovation, increase innovation investment, and advocate for enterprises to uphold the concept of green research and development. It is necessary to increase the introduction of high-tech talents to increase the accumulation of human capital for the improvement of regional green economic efficiency. Promote the transformation and upgrading of industrial structures to provide a deep guarantee for the improvement of green economic efficiency, which can be done through financial support and policy support to help enterprises transform and upgrade. Focusing on the coordinated development of scientific and technological innovation and industrial structure upgrading, only by giving full play to the important effect of the synergistic development of the two and promoting the development of regional green economy from the source can we provide a long-term impetus for the improvement of green economic efficiency.

(3) Construction of pilot projects to promote the greening of the economy Give full play to the positive effect of the pilot policy of green economic development, promote the pilot cities to formulate green development plans according to their actual conditions, and play a leading role in the surrounding areas to form a positive demonstration effect. Give full play to the spatial spillover effect of scientific and technological innovation and industrial structure upgrading on green economic development, tap the green economic efficiency growth points in the new era, and contribute to the realization of green and sustainable economic development It will contribute to the sustainable development of the economy.

There are still shortcomings in the research work of this paper. Although the evaluation index system is selected from multiple perspectives based on the previous research results, the selected indexes cannot comprehensively represent the level of regional scientific and technological innovation, the level of industrial structure upgrading, and the level of green economy efficiency, and there is still room for optimization of the evaluation index system.

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Conflicts of Interest

The authors declare no conflict of interest.

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