Does Technological Innovation Improve the Regional Ecological Efficiency? Empirical Evidence From China

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Title page

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Does technological innovation improve the regional ecological efficiency? Empirical evidence from China

Abstract

The rapid development of China's economy and urbanization has led to the rapid deterioration of the ecological environment. This study aims to explore the relationship between provincial eco-efficiency and technological innovation in China. The DEA model is used to measure the ecological efficiency of 30 regions in China by using the data from 2007 to 2017, and different spatial econometric models were used to explore the influencing factors of ecological efficiency. The results show that in terms of ecological efficiency, the western region has the highest ecological efficiency, and the eastern region has the lowest. However, with the acceleration of urbanization, the ecological efficiency of the three regions gradually declined, and the last three regions basically remained at the same level. Based on spatial econometric analysis, the relationship between technological innovation and ecological efficiency is discussed. The results show that technological innovation has a negative impact on ecological efficiency, which confirms the existence of the environmental Kuznets Curve. In addition, environmental regulation and education level can improve ecological efficiency, while urbanization rate can reduce ecological efficiency. At the same time, spatial spillover effect plays an important role in technological innovation, environmental regulation, education level and urbanization rate in the change of regional ecological efficiency. Policy recommendations for further strengthening environmental protection and sustainable development are discussed.

Key words: Technological innovation; Ecological efficiency; Spatial econometric models; China.

1. Introduction

After the reform and opening-up in the last century, China has made great progress in

economy and has become one of the most important economies in the world. However, the take-off of China's economy is mainly driven by the extensive development mode. The rise of Chinese industrial civilization has brought prosperity, and at the same time, China has become the most serious environmental pollution country in the world. China is currently the largest fossil energy consumer in the world (Cui et al., 2019), and the most polluted country in the world (Yang et al., 2021); Lelieveld et al., 2015). At the same time, other environmental pollution problems such as soil pollution and air pollution have also appeared (Xue et al., 2019; Zhang et al., 2018; Bai et al., 2018; Feng et al 2021). In fact, the problem of ecological environment pollution has become a common concern topic all over the world, and all the world have made corresponding efforts to protect the environment. For example, South Korea took the lead in enacting the basic law on green growth (John and Mathew., 2012). Germany has always focused on the development of "ecological modernization" (jnicke., 2012). In 2012, the Chinese government proposed to integrate ecological civilization construction into the national strategy and formulated relevant laws and regulations. For example, the forest law of the people's Republic of China, the law of the people's Republic of China on the prevention and control of water pollution, and the law of the people's Republic of China on the prevention and control of air pollution, etc. Meanwhile, the Chinese government has committed to achieving peak carbon emissions by 2030 and establishing a national carbon trading market in 2017. Whether from the national strategic level or from the actual situation, attention to environmental issues, accelerating the construction of ecological civilization and improving ecological benefits have attracted the attention of scholars from all walks of life. Technological innovation is often used to explore the relationship between economic growth and the ecological efficiency. With the increasing of resource consumption and environmental problems, the research on ecological efficiency has gradually become the focus of attention, namely, the relationship between economic growth, eco-efficiency and technological innovation (Liu et al., 2020). However, there is little research on the relationship between

technological innovation and ecological efficiency. The existing research on technology
 innovation and ecological efficiency is mostly about the relationship between urban
 technological innovation and ecological efficiency. Therefore, in order to make up for
 the literature blank in this field, this paper constructs the comprehensive evaluation
 index system of ecological efficiency and technological innovation from the
 perspective of technological innovation and ecological efficiency. DEA model and
 spatial econometric model were used to study the correlation effect and spatial effect of
 technological innovation and ecological efficiency in different provinces of China.
 Figure 1 is the theoretical framework of this paper.

Fig 1. Theoretical framework of this paper

2. Literature review

2.1 Ecological efficiency estimations

Theoretically, ecological efficiency is an important index to measure ecological
 construction. It was first proposed by Sturm and Schaltegger (1990), who defined the
 goal of eco-efficiency as the unification of economic value and environmental benefit.
 Ecological efficiency can effectively measure the relationship between economic
 resources and environment, which is vital to evaluate the unified development of

socioeconomic (Govindan et al., 2019; Liu et al., 2020; Wang et al., 2019; Caiado et al., 2017). At present, scholars' research on ecological efficiency mainly focuses on two aspects, the first is about the measurement of ecological efficiency. Some scholars studied the ecological efficiency of regional tourism based on the perspective of China's regional tourism, it is found that the tourism industry and ecology efficiency exist obvious spatial spillover, although it is often considered to be environmentally friendly tourism industry, but in recent years, the rapid growth of tourism has failed to compensate for the destruction of the ecological environment, even if it is the common problem (Sun et al., 2021; Chen et al., 2020). Scholars found that China has achieved a win-win situation of environmental protection and economic growth during the industrial transformation and upgrading in recent years by including industrial wastewater and exhaust emissions in the assessment of ecological efficiency (Shao et al., 2019; Chen et al., 2020). Some scholars also evaluated the provincial ecological efficiency by studying the two subsystems of household pollution control and industrial pollution control, and found that the ecological efficiency of economically developed areas was better than that of economically underdeveloped areas (Zhang et al., 2020). More scholars have studied China's eco-efficiency from a regional perspective (Xue et al., 2021; Ren et al., 2019; Yang et al., 2021). The empirical results show that, in terms of urban eco-efficiency, the regional eco-efficiency in China generally presents a gradually decreasing situation from the east to the west. In terms of the time span, the regional eco-efficiency mainly presents a U-shape.

The second is to explore the factors of ecological efficiency. FDI has a significant impact on ecological efficiency, FDI has a significant impact on ecological efficiency. Specifically, FDI will affect the ecological environment by transferring pollution intensive enterprises to developing countries (Nasir et al., 2019; Pao, H. T., Tsai, C. M., 2011). The impacts of FDI on ecological efficiency are mainly pollution halo effect and pollution sanctuaries. There are discussions about the pollution shelter and pollution halo effect of FDI on regional ecological efficiency (Ren et al., 2020; Tong et al., 2020;

Jun et al., 2018). China's natural gas, electricity and other energy supply industries have higher ecological efficiency than mining and other industries, The main reason for the high eco-efficiency is that China's oil and gas exploration and production areas are under state control (Shao et al., 2019). Scholars also found that the upgrading of industrial structure and educational level generally have a positive impact on ecological efficiency (Han et al., 2021; Huang et al., 2020; Wang et al., 2020; Yasmeen et al., 2020).

2.2 Technological innovation and ecological efficiency

The theory of technological innovation has a long history and has been widely applied (Guo et al., 2021; Vural., 2021; Wang et al., 2020). In 1934, Schumpeter (1934) applied the theory of technological innovation to economic analysis. He proposed that economic growth is an evolutionary process with innovation as the core. Many scholars also studied the relationship between technological innovation and economic growth (Liu and Zhang et al., 2021; Zhou et al., 2021). However, with the aggravation of resource consumption and environmental pollution, people gradually turn their research focus to the study of ecological efficiency, that is, the relationship between economic growth, ecological efficiency and technological innovation (Liu et al., 2020; Deng and Gibson., 2019). At present, most of the literature research is based on the perspective of space to study the relationship between technological innovation and ecological efficiency (Ali et al., 2021; Li et al., 2021). On the relationship between technological innovation and ecological efficiency, scholars' research results are inconsistent. Some scholars believe that technological innovation has a significant negative impact on ecological efficiency, but the interaction between technological innovation and industrial structure can improve regional ecological efficiency (Huang et al., 2020). There are different relationships between technological innovation and ecological efficiency. In the early stage of development, large-scale technological innovation will have a siphon effect on the surrounding areas, while in the middle and late stage of development, technological innovation will have a positive impact on the ecological efficiency of surrounding cities through diffusion effect (Zhang et al., 2018; Hong and

Zhang., 2016). Some scholars have studied the relationship between the two from the national level and found that the impact of technological innovation on the realization of sustainable development is different in countries at different development stages. For middle-income and high-income countries, technological innovation can bring sustainable progress. However, for low-income countries, there is no causal relationship between technological innovation and sustainable development (Ormi, 2020; Ormi, 2018; Surender and Shunsuke, 2010).

3. Research methods

3.1 DEA model

This paper uses DEA model to measure the ecological efficiency of 30 regions in China. Because of its objectivity, DEA is regarded as one of the effective methods to evaluate efficiency. Generally, DEA models are divided into CCR model with fixed scale return and BBC model with variable scale return. Combining CCR model with BCC model, ecological efficiency, pure technical efficiency and scale efficiency of each input index and output index can be determined simultaneously. The specific formula is as follows: Firstly, it is assumed that there are n decision making units, X_j represents the input vector of the j th decision making unit, Y_j represents the output vector of the j th decision making unit, θ represents the efficiency value, and λ represents the weight. The linear programming equation of the CCR model is as follows:

$$\begin{cases} \min \theta \geq 0, \\ s.t. \sum_{j=1}^n X_j \lambda_j \leq \theta X_0, \\ \sum_{j=1}^n X_j \lambda_j \geq Y_0, \\ \lambda_j \geq 0. \end{cases} \quad (1)$$

Adding constraints to weighted λ , a BBC model with variable returns to scale can be established. Its linear programming equation is as follows:

$$\begin{cases} \min \theta, \\ s.t. \sum_{j=1}^n X_j \lambda_j \leq \theta X_0, \\ \sum_{j=1}^n Y_j \lambda_j \geq Y_0, \\ \sum_{j=1}^n \lambda_j = 1, \\ \lambda_j \geq 0. \end{cases} \quad (2)$$

Among them, θ represents the efficiency value of the i th DMU, it's $0 \leq \theta \leq 1$. When $\theta < 1$, The decision unit is represented as an invalid DEA.

3.2 Space panel model

Most of the studies on spatial spillover and correlation effects use spatial econometric models to measure. Generally, spatial econometric models mainly include Spatial Dobbins model (SDM), spatial autoregressive model (SAR) and spatial error model (SEM). Among them, Spatial Dobbins model appears in scholars' literature as a more general model. The spatial autoregressive model and the spatial five error model are all evolved from the Spatial Dobbins model. Then, the SDM model can be presented as follows:

$$eff_{it} = \rho W eff_{it} + x_{it} \beta + W X_{it} \delta + k_i + v_t + \mu_{it} \quad (3)$$

In the formula, eff_{it} is explanatory variable, which means regional eco-efficiency in China; W is space weight matrix, in this paper, we would use 0-1 matrix as the space weight matrix. $W eff_{it}$ is the spatial lag term of ecological efficiency, ρ is spatial autoregressive coefficient. x is the set of core explanatory variables, urban innovation behavior and other explanatory variables; $W X$ is the spatial lag term of explanatory variable and control variable, δ is the corresponding coefficient of each explanatory variable; k_i 、 v_t represent individual and time fixed effects. μ represent random disturbance term. When $\delta = 0$, the SDM model would degenerates into SAR model. When $\delta + \rho\beta = 0$, SDM model degenerates into SEM model.

In this paper, the 0-1 adjacency matrix is chosen as the spatial weight matrix of the spatial econometric model. the matrix is set as follows:

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$$W_{ij} = \begin{cases} 1 \\ 0 \end{cases} \quad (4)$$

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when region i is adjacent to j , $W_{ij}=1$; when region i is not adjacent to j , $W_{ij}=0$.

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4. Results and findings

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4.1 Indicator selection and data source

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4.1.1 Regional ecological efficiency

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In this paper, we choose DEA model to measure regional eco-efficiency of China.

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Firstly, SO_2 、 industrial dust emissions and wastewater emissions are selected as output

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indicators. Because city pollution discharge is the main source of city pollution.

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Secondly, choose labor、 capital and resource as input indicators. Among them, choose

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regional employment at the end of the year as the labor indicator, total fixed asset

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investment by the end of the year as the capital indicator, as for resource indicators,

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choose annual social electricity consumption because of data availability. All the data

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come from *China Statistical Yearbook*, *China City Statistical Yearbook* and *China*

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Science and Technology Statistical Yearbook (2008-2018). Considering the perennial

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absence of data in Tibet, the measurement of Tibet will be excluded in this paper to

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ensure the accuracy of data. And interpolation method is adopted to supplement

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individual default values in other provinces. Detailed index selection is shown in Table

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Table 1. Input and output index system.

System	Detailed indicators	Unit
Output indicators	SO_2 emissions	10^4 tons
	Dust emissions	10^4 tons
	Wastewater emissions	10^4 tons
Input indicators	Electricity consumption	KWH
	Employment	persons
	Investment in fixed assets	yuan

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4.1.2 Spatial econometric model

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(1) Explained variable: The ecological efficiency previously measured by the DEA

model is used as the explained variable, which is marked as eff.

(2) explanatory variable:

technological innovation: Technological innovation is calculated based on multi-dimensional indicators. Based on the scientific, operability and data availability of the indicators, this paper constructs a comprehensive index system of technological innovation, which mainly includes three first-level indicators of innovation environment, innovation input and innovation output and nine second-level indicators. Specific indicators are shown in Table 2.

Environment regulation: There are plentiful literatures demonstrated that the impact of environmental regulation on ecological efficiency (Cheng et al., 2019; Rubashkina et al., 2015), most of them concluded through econometric models that environmental regulation had a positive impact on eco-efficiency, and concluded that there was a U-shaped relationship between environmental regulation, technological innovation and eco-efficiency, which verified the Porter Hypothesis (Porter 1991; Porter and van der Linde 1995). In this paper, we defined environmental regulation as artificial intervention to the environment. Therefore, the proportion of environmental protection personnel in employment, the proportion of environmental expenditure in fiscal expenditure and the harmless disposal rate of household garbage in each region were selected as the indicators of environmental regulation, and a comprehensive index was calculated by TOPSIS method.

Average education years: People's education level will improve people's attention to regional ecology or environmental protection, so the average number of years of education in the region was selected as one of the control variables.

FDI: FDI always considered to promote the economic growth of a region, and FDI has proved to be an important engine for China's economic growth. From empirical experience, it is generally believed that FDI will produce pollution sanctuary effect and pollution halo effect on the ecological environment (Nancy et al 1993). Studies by some scholars show that the impact of FDI on ecological efficiency is different in different

stages of economic development, FDI has a negative impact on ecological efficiency when the level of economic development is low. Only when the economic level exceeds a group of thresholds, FDI can contribute to the improvement of ecological efficiency (Tong et al, 2020). Therefore, we take the proportion of FDI in GDP as one of the indicators

Industrial structure: It is generally believed that industrial structure has a great impact on ecological efficiency. The ecological efficiency of regions with a large proportion of primary and tertiary industries is usually better than that of regions with developed secondary industries. In this paper, we use the location quotient of the output value of the secondary industry in each region as the index of industrial structure.

Urbanization: China is a vast country. In the early stage, the urbanization level of different regions in China varies greatly, but since the Reform and opening-up, all regions in China have accelerated the urbanization process. Generally, urbanization has a negative impact on regional ecological efficiency in China (Tang et al 2020; Yasmeen and Humaira., 2020). Therefore, the urbanization level of each region in China is selected as one of the indicators in this paper.

Table 2. Technological Innovation index system.

Level indicators	The secondary indicators	Unit
Innovation environment	Science and education expenditure/fiscal expenditure	%
	Technology market turnover /GDP	%
	Per capita education expenditure	RMB
	GDP per capita	RMB
Innovation input	R & D investment intensity	%
	Total amount of R & D personnel /R & D personnel	%
Innovation output	New product sales revenue/regional GDP	%
	Number of inventions granted/number of patents granted	%

4.2 Measurement of regional ecological efficiency in Chinese provinces

We have analyzed China's regional ecological efficiency in two aspects. First, we have estimated the ecological efficiency of 30 provinces in China. Second, China is divided into East, central and West according to China's administrative divisions. The regional

ecological efficiency is measured by subregions. The ecological efficiency of these three regions is obtained by averaging the ecological efficiency scores of each division, The results of regional ecological efficiency are shown in Table 3 and Figure 2.

From 2007 to 2010, during China's Tenth Five Year Plan period, China's overall regional ecological efficiency showed a slight downward trend. In this time, the overall ecological efficiency was not high. After 2011, China's ecological efficiency gradually increased, taking 2013 as the inflection point, and then the rising speed gradually accelerated. In 2015, the ecological efficiency of various regions in China peaked.

From the divided regions, there is a large gap in ecological efficiency among the three regions in China, showing a trend of the lowest in the East, the second in the middle and the highest in the West. The change trend of ecological efficiency in the three regions is relatively gentle. From the perspective of provinces, Guizhou and Ningxia Hui autonomous regions have the highest ecological efficiency, while Fujian and Zhejiang have the lowest ecological efficiency. Fujian and Zhejiang are the most developed coastal areas in China. They have a high level of urbanization, developed industry and commerce, and many highly polluting enterprises, which is in line with the actual situation.

However, after the inflection point in 2013, the ecological efficiency of eastern and central China began to show an accelerated upward trend, and the Western China showed a slow upward trend. The gap between the ecological efficiency values of the three regions began to narrow gradually. In 2014, the ecological efficiency gap between the three regions has narrowed to 0.039. By 2015, the ecological efficiency of the central region surpassed that of Western China for the first time, reaching the highest value of 0.96925 in 11 years. Since then, the ecological efficiency value of the central region has been the highest, followed by the western region and the eastern region. Compared with 2007, the gap between the three regions has been greatly narrowed. The possible reason is that the eastern region developed earlier and the urbanization rate is higher. In the early stage of China, many highly polluting enterprises were concentrated,

resulting in the discharge of many industrial polluting wastes and poor ecological environment. On the contrary, the western region is still at a low level of urbanization and development, with a good natural environment and high ecological efficiency. With the implementation of policies such as the development of western China and the rise of central China, the central and western regions began to undertake high-pollution enterprises in the eastern regions, which led to the decline and continuous decline of ecological efficiency in various regions in China in recent years. In 2013, the Chinese government launched a nationwide environmental protection inspection campaign. Lots of productive enterprises with high pollution were punished according to law, resulting in a rapid increase in regional ecological efficiency.

Table 3. Regional ecological efficiency based on DEA.

	Region \ Year	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Easte rn Regio n	Beijing	0.357	0.364	0.37	0.39	0.423	0.39	0.341	1	0.884	0.929	0.805
	Tianjin	0.489	0.398	0.398	0.356	0.399	0.412	0.457	0.895	0.597	0.618	0.671
	Hebei	0.772	0.829	0.725	0.746	1	0.822	0.99	1	1	1	1
	Liaoning	1	1	0.91	0.957	0.916	0.893	0.975	1	1	1	1
	Shanghai	0.362	0.391	0.399	0.317	0.291	0.342	0.369	1	1	1	1
	Jiangsu	0.368	0.362	0.358	0.37	0.361	0.359	0.341	0.691	0.783	0.823	0.78
	Zhejiang	0.265	0.29	0.287	0.243	0.275	0.298	0.332	0.734	0.805	0.82	0.884
	Fujian	0.28	0.292	0.318	0.28	0.277	0.283	0.334	0.495	0.763	0.717	0.71
	Shandong	0.454	0.486	0.473	0.489	0.655	0.673	0.681	0.733	0.866	0.835	0.817
	Guangdong	0.302	0.337	0.359	0.31	0.263	0.304	0.333	1	1	1	1
Cent ral regio n	Hainan	0.493	0.418	0.384	0.319	0.403	0.343	0.338	0.816	0.749	0.855	0.869
	Shanxi	1	1	0.943	0.88	1	1	1	1	1	1	1
	Jilin	1	1	1	0.965	0.908	0.692	0.772	0.922	1	0.844	1
	Heilongjiang	1	1	0.973	1	1	1	1	1	1	1	1
	Anhui	0.564	0.544	0.482	0.471	0.485	0.433	0.464	0.823	1	0.896	0.874
	Jiangxi	0.71	0.676	0.712	0.685	0.912	0.986	0.889	0.916	1	1	1
	Henan	0.673	0.658	0.625	0.641	0.605	0.604	0.665	0.713	0.861	0.736	0.736
	Hubei	0.369	0.347	0.338	0.34	0.374	0.378	0.435	0.845	0.893	0.785	0.781
West regio n	Hunan	0.854	0.715	0.644	0.623	0.556	0.574	0.676	0.903	1	1	1
	Guangxi	1	0.884	0.822	0.89	0.571	0.564	0.604	0.785	1	0.946	0.96
	Chongqing	1	1	1	1	1	1	1	1	0.979	1	1
	Sichuan	0.675	0.615	0.578	0.638	0.524	0.545	0.473	0.689	0.909	0.916	0.926
	Guizhou	1	1	1	1	1	1	1	1	1	1	1
	Yunnan	0.51	0.463	0.432	0.42	0.577	0.602	0.559	0.686	0.909	1	0.907

Shaanxi	0.813	0.776	0.716	0.69	0.857	0.809	0.865	0.846	0.95	0.751	0.737
Gansu	0.711	0.695	0.761	0.83	0.802	0.798	0.81	0.869	0.806	0.668	0.617
Qinghai	0.797	0.995	1	0.815	1	1	1	1	1	0.921	0.95
Ningxia	1	1	1	1	1	1	1	1	1	1	1
Xinjiang	1	1	1	1	1	1	1	0.918	0.815	0.754	0.87
Inner Mongolia	1	1	1	1	0.966	1	0.994	1	1	0.87	0.897

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Fig 2. Eco-efficiency trends in different regions of China

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4.3 Spatial econometric model

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In combination with the availability and operability of the data, ecological efficiency

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was taken as the explanatory variable, and technological innovation, environmental

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regulation, industrial structure, and urbanization rate were taken as the core

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explanatory variables. Descriptive statistical results are shown in the following table

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Table 4. Descriptive statistics of specific variables

Variables	N	mean	sd	min	max
Number	330	15.500	8.669	1.000	30.000
Year	330	2012	3.167	2007	2017
Effi	330	0.756	0.250	0.243	1.000
TI	330	0.292	0.168	0.043	0.847
ENR	330	0.354	0.232	0.001	1.001
Edu	330	0.341	0.207	0.000	1.001
FDI	330	0.053	0.056	0.000	0.268
INC	330	0.940	0.678	0.062	3.226

UR	330	0.336	0.248	0.001	1.001
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As suggested by Anselin (1998), the maximum likelihood method (MLE) is used to estimate the spatial panel model. Before the estimation of the model, the spatial correlation of variables and the selection of the model should be tested. *Moran'I* test was carried out on the average value of the data from 2007 to 2017, and the result showed that the value of Moran index was 0.388 under the 0-1 weight matrix, and the condition was significant under another 1%. Therefore, it is necessary to construct spatial econometric model. The null hypothesis is rejected when the LR test statistics are all 1%, which indicates that the more generalized SDM model is the best form to use the spatial panel. In order to show the results more accurately, the results of SDM, SAR and SEM models are presented, and the results of SAR and SEM are used for comparative analysis.

The results obtained through calculation are shown in Table 5:

Table 5. Spatial panel basic regression results.

	SDM	SAR	SEM
<u><i>LnTI</i></u>	-0.191*** [0.050]	-0.315*** [0.047]	-0.320*** [0.044]
<i>LnEnr</i>	0.108*** [0.017]	0.088*** [0.016]	0.097*** [0.017]
<i>LnEdu</i>	0.044*** [0.013]	0.035** [0.0111]	0.028** [0.011]
<i>LnINC</i>	-0.043 [0.026]	-0.052 [0.029]	-0.051 [0.031]
<i>LnFDI</i>	-0.011 [0.0285]	-0.027 [0.027]	-0.040* [0.0306]
<i>LnUR</i>	-0.0424* [0.019]	0.004 [0.017]	0.002 [0.016]
<i>wLnTI</i>	0.276* [0.121]		

<i>w.LnEnr</i>	0.132***		
	[0.038]		
<i>w.LnEdu</i>	0.079*		
	[0.031]		
<i>w.LnINC</i>	0.038		
	[0.047]		
<i>w.LnFDI</i>	0.034		
	[0.035]		
<i>w.LnUR</i>	-0.108*		
	[0.047]		
<i>ρ / λ</i>	0.395***	0.491**	0.513***
	[0.057]	[0.052]	[0.056]

Note: ***, **, * are significant under the conditions of 1%, 5%, and 10%, respectively. The data in parentheses are P values. Source: Author's estimations.

As we can be seen from Table 5, among all influencing factors, environmental regulation has the greatest positive impact on ecological efficiency, with a ratio of 0.108. Technological innovation was the lowest, with a ratio of -0.191. This means that for each increase of technological innovation, the ecological efficiency will decrease by 0.191. Technological innovation has no positive effect on regional ecological efficiency. The possible reason is that with the increasing pressure of environmental protection in recent years, the intensity of regional innovation research and development has been restrained. From the perspective of space spillover, technological innovation has a positive impact on the ecological environment. The possible reason is that with the increase of inter-regional environmental protection pressure, highly polluting and efficient enterprises may be moved to the surrounding areas, which will not only bear the high pollution of enterprises, but also benefit from enterprises. The surrounding areas can invest economic benefits into R&D innovation, which will lead to the positive impact of surrounding technological innovation on ecological efficiency.

The positive correlation effect of environmental regulation on regional ecological efficiency is the largest, and the specific value is 0.108, which passes the 1% test. The results show that environmental regulation plays a good role in improving regional ecological efficiency. At the same time, the spatial lag term of environmental regulation is also significantly positive, indicating that environmental regulation not only has a good impact on the ecological efficiency of the region, but also has a good impact on the green development of other regions through spillover effect. The average number of years of education also has a positive impact on regional ecological efficiency, with a specific value of 0.0442, passing the 1% test. Its spatial lag term also passed the 1% test, with a specific value of 0.132, indicating that the increase of people's years of education will improve people's environmental awareness, and the improvement of people's overall environmental awareness will also improve the surrounding ecological efficiency through the spatial spillover effect. Both the coefficient of industrial structure and the coefficient of opening to the outside world are negative, but not significant. The urbanization rate is negatively correlated with the regional ecological efficiency, and the spatial spillover term coefficient is also negative, both of which pass the 10% test, and the small coefficients are -0.0424 and -0.108, respectively. This indicates that the urbanization rate will have a negative impact on the regional ecological efficiency, which is also consistent with the actual situation. In recent years, China has been advancing its urbanization process, with the urbanization rate exceeding 50 percent in 2012. The rapid urbanization process will cause damage to the ecological environment, thus reducing the ecological efficiency.

By analyzing the spatial effect of empty panels, the specific results are shown in Table 6:

Table 6. Results of spatial spillover effect

Variables	Coef	Direct	Indirect
<i>LnTI</i>	-0.191** (-3.8)	-0.167** (-2.84)	0.306 (-0.098)
<i>LnEnr</i>	0.108***	0.127***	0.275***

	(-6.39)	(-7.44)	(-5.03)
<i>LnEdu</i>	0.442***	-0.057*	0.153**
	(-3.54)	(-4.01)	(-2.99)
<i>LnINC</i>	-0.011	-0.008	0.043
	(-0.60)	(-0.41)	(-0.79)
<i>LnFDI</i>	-0.043*	-0.399	0.036
	(-1.52)	(-1.46)	(-0.625)
<i>LnUR</i>	-0.042***	-0.057**	-0.199*
	(-4.87)	(-2.61)	(-2.48)

According to the analysis results, the direct effect of technological innovation on ecological efficiency is negative and has passed the 1% test, but the indirect effect is not obvious. The possible reason is that China has gradually strengthened the awareness of ecological environment protection in recent years. The punishment for the enterprises with high pollution affecting the ecological environment is increased, which restrains the research and development of technological innovation, leading to the negative impact of technological innovation on the ecological efficiency of the region. Environmental regulation has a significant positive impact on the ecological efficiency, which not only has a good impact on the regional ecological efficiency but also has a spillover effect on the surrounding areas. The average length of education of residents has a good effect on the ecological efficiency, the direct effect is negative, but the more obvious is a positive indirect effect. The possible reason is that with the increasingly perfect regional transportation system in China, there are more exchanges between different regions, and the increase of residents' years of education has produced a greater spatial spillover effect. The direct and indirect effects of FDI and industrial structure are not significant. The direct and indirect effects of urbanization rate have passed the test of 5% and 10% respectively, and the coefficient is negative. It shows that urbanization has a negative effect on regional ecological efficiency, which is consistent with the actual situation. Although China's urbanization has promoted economic development and the optimization and upgrading of industrial structure, it has also brought a series of ecological and environmental problems, such as urban heat island effect, haze effect, congestion effect and garbage effect.

4.4 Discussion

An interesting finding is that, at the beginning of the study in 2007, China's regional ecological efficiency was not high and even showed a downward trend, which was inseparable from the extensive economic development mode of that year (Wang and Feng., 2020). During the period of the tenth Five-year Plan (2006-2010), When China's social economy was in the stage of rapid development, there was no clear limit on the emission of environmental pollutants, and the economic development in this period was at the cost of environmental pollution (Wang and Feng., 2021). Since 2011, China has entered the 12th Five-Year Plan period. During this period, Chinese leaders put forward a long-term plan for the country's overall industrial transformation and upgrading from extensive development to intensive development under the impetus of domestic and foreign factors (Liu et al., 2020). Since 2012, China's regional ecological efficiency has been gradually increasing. This is because the 18th National Congress of the Communist Party of China in that year identified ecological civilization construction and the realization of sustainable development as an important national strategy. At the same time, the eastern region, China's economic center of gravity, has accelerated industrial transformation and upgrading, the relocation of highly polluting enterprises and environmental pollution control. In 2015, the Chinese government established the Central Environmental Inspection Team (Tan and Mao., 2020). The main purpose is to monitor the strict implementation of pollution control measures by enterprises. Therefore, since 2015, the eco-efficiency of all regions has maintained a high level, forming a peak in this period.

Another interesting finding is that although technological innovation has a negative impact on the improvement of ecological efficiency, environmental regulation has a significant positive impact on the improvement of ecological efficiency, which is also consistent with the views of some scholars (Guo et al., 2017). They believe that environmental regulation can promote technological innovation and thus promote regional green growth performance. At the same time, the development of urbanization will have a negative impact on ecological efficiency, which is consistent with the

Proposal of "Paris Agreement" to control the scale of urbanization as one of the measures to protect the ecological environment (Yasmeen and Humaira). This is because the development of urbanization means changes in land use, population living, production and lifestyle. FDI has a negative impact on ecological efficiency because China's economy has been at a low level for a long time. Foreign direct investment is more about introducing pollution intensive enterprises into China. The rapid and low-quality development leads to the "pollution paradise hypothesis" (Tong et al., 2020; Nasir et al., 2019; Shahbaz et al., 2015).

5. Conclusion and policy suggestions

In this article, we constructed a scientific regional ecological efficiency evaluation model including output indicators and input indicators, and calculates the regional ecological efficiency of various provinces and regions in China by DEA model. Then, the relationship between ecological efficiency and technological innovation and other control variables is analyzed by spatial econometric model. The empirical results show that the regional ecological efficiency is Gradually decrease from Western China to Eastern China. With the development of China's industrialization, the highly polluting industries in the developed eastern regions are gradually transforming to those in the central and western regions, resulting in the improvement of ecological efficiency in the eastern region year by year. The ecological efficiency of the central and western regions has gradually decreased, and the gap between the three has gradually narrowed. In the second stage, the spatial econometric model is used to analyze the main factors affecting regional ecological efficiency in China. The results show that there is a significant spatial spillover effect in China's regional ecological efficiency. Innovation has a significant negative impact on ecological efficiency. With the pressure of environmental protection in various regions, technological innovation has a positive impact on the ecological efficiency of surrounding areas. Environmental regulation is the most effective means to improve ecological efficiency. In addition, the main factors affecting ecological efficiency are the length of education of local residents and the

460 efficiency of urbanization. These influencing factors will have a certain spatial spillover
461 effect, which will not only affect the region, but also have a spillover effect on the
462 surrounding areas.

463 The above conclusions have the following suggestions and Enlightenment: first, we still
464 pay attention to the management of technological innovation and the direction of
465 guiding technological innovation in the ecological environment. Not only in terms of
466 input, but also in terms of output, we need to pay attention to promote the application
467 of technological innovation in ecological environment governance. Give policy support
468 from the three dimensions of innovation environment construction, innovation output
469 and innovation investment. We will strengthen the protection of invention patents,
470 simplify administrative examination and approval procedures, and accelerate the
471 popularization and application of patent achievements. In order to give full play to the
472 leading role of technological innovation in regional ecological environment protection
473 and promote national green development. Second, speed up the development process
474 of technological innovation, better match the governance of regional ecological
475 efficiency, create good conditions for the spillover effect of technological innovation,
476 expand the scope of spillover effect, comply with China's current urban agglomeration
477 development strategy, and accelerate out of the "U-shaped line" transition zone. Third,
478 pay attention to the coordination between technological innovation and other regulatory
479 factors, and create a good technological innovation environment. For regions with
480 relatively developed and balanced economic development in eastern and southeastern
481 China, we should pay attention to accelerating the research and development of green
482 intelligent manufacturing technology, modern energy technology and the application of
483 key technologies. For regions with unbalanced economic development in Western
484 China, such as external spillovers, we should accelerate the innovation space to improve
485 the overall innovation ability of the region, promote coordinated regional and urban
486 economic development and green transformation. Fourth, in terms of the impact of
487 other control variables, we should reasonably control China's urbanization process; For

foreign direct investment, we need to strengthen supervision, improve the quality of foreign investment introduction, and promote the realization of China's sustainable development.

Authors' Contributions Huan Huang: Conceptualization, Investigation; Jiaxin Kuang: Methodology, Writing-review & editing, Roles/Writing-original dra; Fan Wang: Formal analysis, Validation; Ke Tian: Visualization, Software; Supervision; Yi Xiao: Data curation, Project administration, Resources.

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Data availability The datasets used during the current study are available from the corresponding author on reasonable request.

Compliance with ethical standards

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