



Influencing factors of environmental efficiency of strategic emerging industries and their power cooperation mechanism design

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Abstract

We investigate the influencing factors of environmental efficiency of strategic emerging industries (SEIs) and cooperative game mechanism design amongst diversified actors by using China's provincial panel data from 2004 to 2019. Firstly, we find that the following factors improve the environmental efficiency of SEIs: rationalisation of the industrial structure, proportion of the tertiary industry, government's ability to intervene in the economy and fairness and integrity of environmental law enforcement. Conversely, factors, such as intensity of ecological construction and environmental regulation, hamper the environmental efficiency of SEIs. Secondly, evolutionary game analysis indicates that the behavioural strategies of game decision-making subjects depend on the behavioural decisions of the relative actors, social supervision and government regulation, which work together in influencing the environmental efficiency of SEIs. *{innovation, supervision}* is the optimal equilibrium state of the game. Thirdly, simulation results show that in the absence of government regulation, foreign direct investment (FDI) slows down the speed of firms tending to the equilibrium state of green innovation. The potential gain and loss of social supervision on corporate behaviour is an important factor affecting government behaviour decision making. Governments prefer punishment tools in environmental regulation, therefore influencing noninnovative firms in SEIs. We contribute to prior works by unifying various policy tools into the same econometric model framework based on an evolutionary game model.

Keywords SEIs · Environmental efficiency · Influencing factor · Evolutionary game · Numerical simulation

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Introduction

With the world in the post-COVID-19 era, countries worldwide urgently need to transform their economic growth patterns through industrial restructuring to escape the haze of the pandemic as soon as possible and achieve a new round of economic growth. Industrial policy is a crucial government-implemented tool which affects the catch-up progress of high-tech latecomers amongst developed countries (Gerschenkron 2015) in view of the neo-Schumpeter framework (Nelson and Winter 1982). Extensive development models lead to excessive energy consumption, depletion of limited energy sources and deterioration of the beautiful environment (Lundgren et al. 2016). Countries are developing strategic emerging industries (SEIs), improving the environmental efficiency of SEIs (Feichtinger et al. 2016), accelerating the adjustment and upgrading of the industrial structure, transforming the economic growth mode and nurturing new development momentum. Ultimately, the common goal of

the current academic community, governments and firms is to promote and lead economic transformation development and high-quality growth (Sun et al. 2017; Vasanthakumar et al. 2016).

In China, the economic growth model has changed from being driven by resource input to being driven by innovation and technology. The development of a resource-saving and environment-friendly economy may be an important guarantee for sustainable economic development in the future. The central government proposed China's SEIs and includes seven major industries, namely new generation IT, high-end equipment manufacturing industry, new materials, biology/biotechnology, new energy automobiles, new energy, energy conservation and environmental protection and the development of which has aimed at addressing growing socioeconomic and environmental challenges in China and is a central part of China's state-led catch-up strategy after the 2008 global financial crisis. Therefore, promoting the 'qualitative' and 'quantitative' development of SEIs is an inevitable requirement and an important approach for the high-quality development of the future global economy.

Substantial literature has discussed the determinants of the environmental efficiency of SEIs from different perspectives. In the macro level, Ellison et al. (2010) find that the series of fiscal and financial support policies and technological innovation mechanisms from local governments are important factors that affect the environmental efficiency and sustainable development of SEIs. However, it depends on the preference of local governments in balancing short-term interest and long-term development, as Chen et al. (2022) find that elevated local government debt exacerbates corporate financial constraints, which ultimately weaken the green innovation ability of companies whilst creating large financial risks. Huang et al. (2022) show that environmental policy uncertainty leads firms to reduce their green patent applications, and such effect is more pronounced in nonstate-owned enterprises. In the meso aspect, Erzurumlu and Erzurumlu (2013) contend that market and regulatory drivers affect environmental efficiency. Intensified market competition has a negative effect on firms' environmental performance, whereas firms cannot escape competition via environmental differentiation (Duanmu et al. 2018). However, Flammer (2015) also finds that domestic firms respond to tariff reductions and more international competitors by increasing their environmental investment. In the micro perspective, several stakeholders of the firms in SEIs also influence their environmental efficiency. Stakeholders, including local universities, investors, supply chain partners' demand or customers' sophistication influence the environmental efficiency of SEIs (Eesley et al. 2016; Huang and Chen 2022; Qing et al. 2022a, b).

Potential gaps arise because unifying various policy tools into the same econometric model framework in related fields

is difficult when studying the environmental efficiency of SEIs. As more economic researchers are interested in examining the interplay amongst varied levels of analysis, the multilevel lens is considered the potential tool to bring in new understanding by integrating micro- and macro-level evolution within a unifying framework. Limited attention has been paid to the dynamic game relationship (i.e. using frameworks of game theory) amongst several external factors and environmental efficiency of SEIs. In addition, existing literature normally uses the traditional DEA or the classic C-D model (Dan 2016; Sun et al. 2017; Miao et al. 2018; Luo et al. 2019) to examine environmental efficiency, and the effectiveness and accuracy of these models are meaningful to test in emerging economies.

The aim of our work is to evaluate further the environmental efficiency of SEIs under environmental constraints and provide a comprehensive view for discussing current industrial development, enterprise production and government planning. As China is at a critical period of transforming new and old kinetic energy, the contradictions between resources, environment and energy in the world are becoming increasingly prominent under the constraints of resources and environment. It is meaningful to explore the cooperation mechanism of the environmental efficiency power main body of SEIs, which has great practical significance and theoretical value to guide the development of SEIs in China and other countries (Miao et al. 2018).

To this end, this study conducts an in-depth investigation of the influence of several different factors and their combination on the environmental efficiency of SEIs in the framework of game theory. Moreover, the study reveals the different implementation strategies on different aspects of environmental efficiency and digs out the optimal implementation strategy of the related policy that can not only effectively increase industrial environmental technology efficiency but also improve the environmental total factor efficiency in SEIs. Specifically, from the perspective of resources and the environment, conducting an objective research and analysis of the factors affecting the environmental efficiency of SEIs and the cooperation mechanism of main power bodies can expand the research field of SEIs and enrich the research results on SEIs under environmental constraints. We develop prior studies on the SEIs and sustainable industrial development by providing the cooperative game mechanism analysis framework of power main body of SEIs as well as the measurements of the environmental efficiency.

The contributions of this paper are as follows: Firstly, prior literature has discussed the determinants of environmental efficiency in SEIs from different perspectives (Ellison et al. 2010; Chen et al. 2022; Huang and Chen 2022; Qing et al. 2022a; Qing et al. 2022b) but ignore the dynamic game relationship (i.e. using frameworks of

game theory) amongst several external factors in multiple levels and environmental efficiency of SEIs. How to unify various policy tools into the same econometric model framework has always been a difficult point in related fields. Thus, this study comprehensively examines the factors affecting the environmental efficiency of SEIs, thereby providing important empirical evidence for guiding the development of SEIs.

Secondly, we develop an effective measurement tool of environmental efficiency. Whilst existing literature normally uses the traditional DEA or the classic C-D model (Dan 2016; Sun et al. 2017; Miao et al. 2018; Luo et al. 2019) to examine environmental efficiency, the effectiveness and accuracy of these models are meaningful to test in emerging economies. Instead, this study uses the new slack-based measure (SBM) directional distance function and the Global Malmquist–Luenberger index to measure the environmental efficiency of China's SEIs. The panel Tobit model is adopted to analyse the influencing factors of environmental efficiency of SEIs from the macro, meso and micro perspectives, and the influencing factors of the environmental efficiency of SEIs are comprehensively investigated, thus providing important empirical evidence for guiding the development of SEIs.

Finally, to the best of our knowledge, ours is the first empirical study to discuss the influencing factors of environmental efficiency on the basis of an evolutionary game model. Specially, we analyse the effective cooperation mechanism of government, firm and social supervision to promote the improvement of environmental efficiency jointly and the use of numerical simulation to analyse the specific influence of each parameter on the behaviour decision of the diversified actors. We subdivide into eight types of impact indicators according to the influencing factors of SEIs and construct three driving forces. We also reveal the influence mechanism of dynamic subjects on the environmental efficiency of SEIs and the game evolution between them by establishing a game model. Furthermore, the dynamic evolution process between dynamic subjects is verified through numerical simulation. The corresponding development countermeasures are proposed to provide theoretical reference for the sustainable development, low-carbon development, circular development and green development of SEIs.

The rest of this study is structured as follows: Sect. 2 presents a review of the existing literature on the environmental efficiency of SEIs. Section 3 provides the influencing factors of environmental efficiency of SEIs. Section 4 analyses the cooperation mechanism of the environmental efficiency power main body of SEIs. Section 5 concludes and provides the policy implications.

Literature review

Definition of SEIs

Academic circles have not formed a consensual view for the definition of emerging industries (Porter 1996; Low and Abrahamson, 1997; McGahan 2004). Kesting et al. (2010) believe that an emerging industry refers to a newly developed industry or an industry that re-emerges after an existing industry has been adjusted. Duchesneau and Gartner (1990) believe emerging industries have many uncertainties, and that no rules and experiences are followed in the market and that they can only grow by their exploration. Färe et al. (1994) believe that emergingness usually refers to new sectors and industries where new scientific research and new technological inventions and applications appear. Their technologies, products, equipment, services and markets are still at the growth stage. Emerging industries drive economic and social development through technological progress and form new economic growth points. Teece (1991) points out that the characteristics of scale and scope economy, learning economy and network economy exhibited by strategic industries make them more competitive. In general, SEIs should be based on major technological breakthroughs, the frontiers of current world technology and low-carbon economic development. It has a broad market space and development potential, can drive the rise of some key industries, is related to the long-term development of the national economy and has a strategic guiding role in optimising and upgrading the national industrial structure. In China, new-generation IT, high-end equipment manufacturing industry, new materials, biology/biotechnology, new energy automobiles, new energy, energy conservation and environmental protection are some of the SEIs currently being developed.

Environmental efficiency measurement of SEIs

Färe et al. (2007) consider environmental efficiency a production possibility set containing good and bad outputs. For the production sector, environmental efficiency maximises positive output and minimises negative output (environmental pollution) when considering environmental pollution and given factor inputs. Richter (1966) uses the Laspeyres index formula to estimate total factor productivity. Caves et al. (1982) introduce the Malmquist index to measure production efficiency. Färe et al. (1989) apply the Malmquist index to measure production efficiency amongst regional countries. Hu and Wang (2006) adopt the DEA model with constant returns to scale.

Zhou et al. (2006) simulate environmental performance using the DEA technique slack-based efficiency method and build a model by measuring CO₂ emissions to identify an appropriate method for measuring environmental performance. Zhou et al. (2008) present a perspective on applying DEA models in energy and environmental assessment. Førsund (2008) introduces the material balance principle into environmental efficiency evaluation and examines a complementary input taxonomy to measure the effects of undesirable residuals and expected outputs. Oh (2010) introduces undesired output based on the global production possibility set and directional distance function and proposes a new productivity growth rate indicator with environment-sensitive characteristics, the Global Malmquist-Luenberger index, which focuses on analysing the cumulative trend of changes in production efficiency. Murty et al. (2012) propose an approach using two sub-techniques to account for the high-cost disposition of bad outputs and the free disposition of good outputs. Wang et al. (2013) improve traditional DEA methods by including desired and undesired outputs in the model and use window analysis techniques to analyse cross-sectional and time-varying data. To explore the effects of random factors on environmental efficiency, Jin et al. (2014) establish a stochastic environmental DEA model. Serra and Lansink (2014) study the risk impact of agricultural technical efficiency by extending the order efficiency score to a state transition framework. Woo et al. (2015) examine the environmental efficiency of renewable energy in 31 OECD countries from static and dynamic perspectives using the DEA methodology and the Malmquist Productivity Index. The current trend is that an increasing number of studies use improved slack-based DEA models to assess environmental efficiency, which contains undesirable output variables (Chang et al. 2013; Song et al. 2013). In the measurement of industrial environmental efficiency. Pittman (1983) first attempts to introduce wastewater and waste gas as undesired outputs into the efficiency evaluation framework and measures the effects of pollution control behaviour on environmental efficiency in the Wisconsin paper-making enterprises in the USA. To solve the black box problem of the DEA model, Tone (2001) proposes an SBM model based on slack variables. This model puts the slack variable directly into the objective function, a nonradial and nonangular efficiency measurement method, thereby avoiding the deviation caused by radial and angular selection. Furthermore, Tone and Sahoo (2003) propose an SBM model considering undesired output, which can better fit the relationship amongst input, output and pollution emissions in the measurement of agricultural environmental efficiency. Hayami (1969) proposes a coproduction function to measure agricultural environmental efficiency. McMillan et al. (1989) believe that agricultural total factor

productivity increased rapidly in the early stage of China's reform and opening up, whereas agricultural total factor productivity in the planned economy was stagnant. Chen and Gong (2021) use different methods to analyse and judge China's agricultural total factor productivity. In the measurement of manufacturing environmental efficiency, Hossain and Karunaratne (2004) use the SFA method to measure the technical efficiency of 25 manufacturing industries in Bangladesh, and the results show that (R&D) input was positively correlated with technical efficiency. Arcos and De Toledo (2009) use the data of Spanish electric power enterprises from 1987 to 1997 and find that the technical efficiency of enterprises showed a scale effect, that is, the larger the scale of enterprises, the higher the technical efficiency and the more evident the technological progress.

Therefore, most of prior studies uses the SBM directional distance function and Global Malmquist-Luenberger to measure the environmental efficiency of China's SEI and decompose the environmental total factor efficiency index into technological progress and improvement index.

Factors affecting environmental efficiency of SEIs

Ellison et al. (2010) believe that the series of fiscal and financial support policies and technological innovation mechanisms formulated by the state are important factors that affect the environmental efficiency and sustainable development of SEIs. Løvrdal and Neumann (2011) find that government support and technological innovation restrict the rapid development of emerging marine industries. Some scholars believe that government subsidies replace R&D investment (Lach 2002). Most scholars believe that government subsidies only play the role of attracting new ideas and can only promote the R&D expenditure of enterprises (Busom 2000). Erzurumlu and Erzurumlu (2013) report that operational, market and regulatory drivers affect environmental efficiency. Innovative product exports and local market digestion impact the environmental efficiency of SEIs. Exports can promote the large-scale production of enterprises, resulting in learning by doing and market competition effects. Albort-Morant et al. (2016) believe that enterprises' dynamic and static capabilities affect enterprises positively and directly. Hrovatin et al. (2016) point out that energy cost share, market share and export orientation have a significant effect on environmental efficiency. Miao et al. (2018) find that technological innovation has a significant positive driving effect on the environmental efficiency of SEIs, and the overall development trend displays a steady growth yearly. The influencing factors of environmental efficiency are multifaceted and comprehensive (Li et al. 2017a, b). Multidimensional factors, such as technology, system and values, should be analysed in analysing influencing factors.

In addition, most of the literature on environmental efficiency starts from the perspective of labour, human capital and capital stock. However, the macro, meso and micro factors, especially the effects of these factors on technological innovation, have not been considered.

As more economics researchers become interested in examining the interplay amongst varied levels of analysis, the multilevel lens is considered the potential tool to bring in new understanding by integrating micro-, meso- and macro-level evolution within a unifying framework in analysing the dynamic game amongst several stakeholders of firms and specific sectors. The environmental economics field is faced with market failure and system failure, especially multiple failures in the process of economic system transformation, which provides nourishment and space for the existence and development of diversified policy tool combination. Although research on the combination of supply-side and demand-side policy tools is relatively abundant, they ignore the dynamic game relationship (i.e. using frameworks of game theory) amongst several external factors and the environmental efficiency of SEIs; only a few of them pay attention to the policy-mixed-effect and the possible policy-cross-effect on the environmental efficiency of SEIs at the same time. We further evaluate the environmental efficiency of SEIs under environmental constraints and provide a comprehensive view for discussing current industrial development, enterprise production and government planning.

Analysis of influencing factors of environmental efficiency of SEIs

Model

This study takes the environmental efficiency of SEIs as the explained variable. On the basis of existing research, 10 influencing factors are selected as explanatory variables, a model is established, and regression analysis is conducted to explore the influencing factors of the environmental efficiency of SEIs. The environmental efficiency of SEIs and decomposed efficiency values are part of the truncated discrete distribution data. Therefore, this study establishes the following Tobit model:

$$Y_{it}^* = \beta X_{it} + u_i + \epsilon_{it} \tag{1}$$

$$Y_{it}^* = \begin{cases} Y_{it} & \text{if } Y_{it}^* > 0 \\ 0 & \text{if } Y_{it}^* \leq 0 \end{cases} \tag{2}$$

In Formula (1), Y_{it}^* is the potential dependent variable, and thus Y_{it} is the actual observed value. The latent variable is observed when it is greater than 0 and takes the value of Y_{it} and is truncated at 0 when it is less than or equal to 0. X_{it} is

the independent variable vector of the influencing factors. β is the coefficient vector. u_i is the individual fixed effect. The error term ϵ_{it} is independent and normally distributed: $\epsilon_{it} \in (0, \sigma^2)$. This study examines environmental efficiency from the perspectives of environmental technical efficiency (GT) and total factor environmental efficiency (GM). We also decompose total factor environmental efficiency (GM) into technology improvement (GTC) and efficiency improvement (GEC). The following models measure GT, GM, GTC and GEC.

Variables and description

Explained variables

This study constructs the environmental technical function and the SBM directional distance function to measure the environmental technical efficiency. Moreover, this study constructs the Global Malmquist–Luenberger index to determine the total factor environmental efficiency and its technical improvement and efficiency improvement values.

Environmental technical function This study constructs a production possibility set that includes expected outputs, such as economics, and undesired outputs, such as environmental pollution. That is, assuming that each decision-making unit (DMU) uses N inputs, $x = (x_1, x_2, \dots, x_N) \in R_N^+$ produces M expected outputs $y = (y_1, y_2, \dots, y_M) \in R_M^+$, and discharge I kind of undesired output $b = (b_1, b_2, \dots, b_I) \in R_M^+$. In each period $t = 1, \dots, T$, the input and output values of the $k = 1, \dots, K$ industries are $(x^{k,t}, y^{k,t}, b^{k,t})$. Denote the set of production possibilities with $P(x)$.

$$P(x) = \{(y, b) : x \text{ can produce } (y, b)\}, x \in R_N^+ \tag{3}$$

The production possibility set $p(x)$ satisfies the following assumptions: closed and convex sets; input and ‘good’ output can be freely handled: if $(y, b) \in P(x)$ and $y' \leq y$ or $x' \geq x$, then $(y', b) \in P(x)$, $P(x) \subseteq P(x')$; joint weak disposability: if $(y, b) \in P(x)$ and $0 \leq \theta \leq 1$, then $(\theta y, \theta b) \in P(x)$; and zero associativity: if $(y, b) \in P(x)$ and $b = 0$, then $y = 0$.

SBM directional distance function On the basis of Tone (2001), an SBM-DEA model that considers undesired outputs is constructed. The SBM model can consider input and output and effectively solve the slack problem of excessive input and insufficient output. The SBM model measures the inefficiency of the evaluated unit by maximising the average degree of improvement of each input (output). The SBM model is more accurate than the directional distance function DEA model. Its linear programming model is shown in Eq. (4).

$$\rho^* = \min \frac{1 - \frac{1}{M} \sum_{m=1}^M \frac{s_{m0}^x}{x_{m0}}}{1 + \frac{1}{s_1 + s_2} \left(\sum_{r_1=1}^{s_1} \frac{r_{r_1 0}^g}{r_{r_1 0}^g} + \sum_{r_2=1}^{s_2} \frac{r_{r_2 0}^b}{r_{r_2 0}^b} \right)}$$

$$S.T. \begin{cases} \sum_{n=1}^N z_n x_{nm} = x_{m0} + s_{m0}^x \\ \sum_{n=1}^N z_n y_{r_1 n} = y_{r_1 0} - s_{r_1 0}^g \\ \sum_{n=1}^N z_n b_{r_2 n} = b_{r_2 0} + s_{r_2 0}^b \\ s_{m0}^x \geq 0, s_{r_1 0}^g \geq 0, s_{r_2 0}^b \geq 0, z_n \geq 0 \\ s_{m0}^x s_{r_1 0}^g s_{r_2 0}^b \end{cases} \quad (4)$$

Model (4) is an SBM model that considers undesired outputs and can be computed using a linear transformation model. If $\rho^* = 1$ (which means all slack variables are 0), then the DMU is effective considering the undesired output. The slack amount of s_{m0}^x is input (reduction of possibility). $s_{r_1 0}^g$ is the expected output relaxation (possible increase). $s_{r_2 0}^b$ is the slack variable of undesired output (possible reduction). The subscript $_0$ represents the decision unit in the estimation model. Vector of non-negative multipliers in Z_n linear programming.

Global Malmquist–Luenberger index model On the basis of Tone (2001) and Choi et al. (2012), the directional distance function is constructed.

$$\bar{D}_0 = (x, y, b; g_y, g_b) = \text{Max} \{ \beta : (y + \beta g_y, b - \beta g_b) \in P(x) \} \quad (5)$$

where $P(x)$ is the production possibility set, and $g = (g_y, g_b)$ is the directional vector. After the input combination is given, the set directional vector is used as the weight to maximise the ‘good’ output (y) and minimise the ‘bad’ output (b).

We refer to the Malmquist productivity change index developed by Färe et al. (2001) and Pastor and Lovell (2005) to examine the productivity changes in two adjacent periods. The GM index is decomposed into the technology progress (GTC) and efficiency improvement (GEC) indices. Let x_t and y_t represent the input and output vectors of period t , respectively, and t is a discrete parameter variable. Then, the Malmquist productivity index can be expressed as follows:

$$M(y_{t+1}, x_{t+1}, y_t, x_t) = \left[\frac{D^t(x_{t+1}, y_{t+1})}{D^t(x_t, y_t)} \times \frac{D^{t+1}(x_{t+1}, y_{t+1})}{D^{t+1}(x_t, y_t)} \right]^{\frac{1}{2}} \quad (6)$$

where $D^t(x_t, y_t)$ and $D^t(x_{t+1}, y_{t+1})$ respectively indicate the evaluated validity of DMU in periods t and $t + 1$ under the technical benchmark based on the t period. $D^t(x_{t+1}, y_{t+1})$ and $D^{t+1}(x_{t+1}, y_{t+1})$ respectively indicate the evaluated validity of DMU in periods t and $t + 1$ under the technical benchmark based on the $t + 1$ period. If $M(y_{t+1}, x_{t+1}, y_t, x_t) > 1$, then the production efficiency of the evaluated DMU has

improved; otherwise, it has decreased. However, given that the Malmquist productivity index adopts the geometric mean form, the index does not have cyclic multiplication, can only analyse the short-term changes in production efficiency in adjacent periods and cannot observe the long-term growth trend of production efficiency.

The Global Malmquist exponent proposed by Pastor and Lovell (2005) satisfies the cyclic multiplicative property and avoids the LP unsolvable problem. Based on the Global Malmquist method proposed by Pastor and Lovell (2005), this study decomposes the global total factor efficiency growth index Global Malmquist into GEC and GTC, as shown in Formula (7).

$$GM_c^G(x_t, y_t, x_{t+1}, y_{t+1}) = \left[\frac{D_c^{t+1}(x^{t+1}, y^{t+1})}{D_c^t(x^t, y^t)} \right] \times \left[\frac{D_c^G(x^{t+1}, y^{t+1})}{D_c^{t+1}(x^{t+1}, y^{t+1})} \times \frac{D_c^t(x_t, y_t)}{D_c^G(x_t, y_t)} \right]$$

$$= \frac{TE_c^{t+1}(x^{t+1}, y^{t+1})}{TE_c^t(x^t, y^t)} \times \left[\frac{D_c^G(x^{t+1}, y^{t+1})}{D_c^{t+1}(x^{t+1}, y^{t+1})} \right]$$

$$= GEC_c \times \left\{ \frac{GTC_c^{G,t+1}(x^{t+1}, y^{t+1})}{GTC_c^{G,t}(x^t, y^t)} \right\}$$

$$= GEC_c \times GTC_c \quad (7)$$

The environmental total factor efficiency GM_c^G can be decomposed into the product of two factors. Amongst them, $\frac{D_c^{t+1}(x^{t+1}, y^{t+1})}{D_c^t(x^t, y^t)}$ represents the change in technical efficiency from t to $t + 1$, and GEC_c represents the change of efficiency value. If $GEC_c^{t+1} > 1$, then, between t and $t + 1$, the DMU moves toward the frontier, thereby improving the efficiency of production activities; otherwise, the efficiency regresses, and the DMU deviates from the frontier. $GTC_c^{t+1} > 1$ means that compared with the production technology in the previous period t , the production technology in the $t + 1$ period has progressed and is closer to the global production technology set; otherwise, the technology has regressed.

It considers the high-tech characteristics of SEIs, the availability of data, the consistency of data statistics and the effectiveness of indicator analysis. Input and output variables are set in the measurement of environmental efficiency. Generally, input variables include capital input, labour and technology input. The output variable set contains variables for ‘good’ output and ‘bad’ output, desired output and undesired output. Desired output is industrial or economic added value, and undesired output is pollution, including solid, gas and liquid pollution, that occurs in the production process. Therefore, three input elements are assumed to be required in the production process, namely, capital input, labour force and technical input. Output is composed of expected output (industrial growth, technological growth) and undesired output (SO_2 , COD , CO_2 wastewater discharge and other environmental pollutant emissions). The specific indicators are shown in Table 1 below.

Table 1 Indicators for measuring environmental efficiency of SEIs

	Variable	Indicator	Description
Input	Capital	Fixed asset investment	It uses the fixed asset investment price index as the conversion coefficient and converts it into a constant price index with 2004 as the base period
	Labour	Number of employees	It uses the annual average number of employees
	Technical	Energy Consumption	It adopts the internal expenditure of R&D funds and converts it to the constant price with 2004 as the base period by the GDP conversion index
Expected output	Industry growth	Gross industrial output	It takes the GDP index of the past years as the conversion coefficient and converts it into the constant price with 2004 as the base period
	Technology growth	Invention patents	It adopts the annual number of invention patents
Unexpected output	Environmental pollution	Soot emissions	It refers to the weight of particulate matter emitted during the production process
		SO ₂ emissions	SO ₂ in the exhaust gas is the main monitoring indicator of environmental regulation in China. SO ₂ emission (KG) = Y mg/m ³ * exhaust gas emission volume (m ³) * 1/1000000
		CO ₂ emissions	No direct data is currently available. It can be calculated by the correlation method. CO ₂ emissions = energy consumption * 0.68 * 3.67, the unit is 10,000 tons
		COD emissions	COD in wastewater is the main monitoring indicator for environmental regulation in China

The above data are at the provincial level. SEIs include seven major industries: new generation IT, high-end equipment manufacturing industry, new materials, biology/biotechnology, new energy automobiles, new energy, energy conservation and environmental protection

Table 2 Descriptive statistical results of environmental efficiency variables of SEIs

Variable	N	Mean	Standard deviation	Min	Max
GT	404	0.439	0.028	0.372	0.469
GM	404	1.031	0.104	0.781	1.214
GTC	404	1.011	0.136	0.643	1.346
GEC	404	1.039	0.097	0.92	1.211

This study calculates the environmental efficiency of SEIs, and Table 2 reports their descriptive statistical results. The table shows that under environmental constraints, the mean values of GT and GM of SEIs in the province are 0.439 and 1.031, the standard deviations are 0.028 and 0.104, the minimum values are 0.372 and 0.781, and the maximum values are 0.469 and 1.214, respectively. These results indicate that GT and GM had a fluctuating upward trend and that the provinces had differences, but the overall environmental efficiency level is low. The efficiency and technological improvement of the subindicators of environmental total factor efficiency vary amongst provinces, and the overall level is also low.

Economic development level Economic development level (Eco) is measured directly using the logarithm of GDP per capita in each province. With the improvement of economic

development, residents' awareness of ecological and environmental protection has been enhanced continuously, the production process of products has become more stringent, and the consumer demand for green products is increasing. Most SEIs are green industries. Therefore, the concept of residents' green consumption is conducive to increasing the product demand for SEIs, providing financing needs for technological innovation in SEIs, promoting green technology innovation, reducing the ecological and environmental costs of its development and promoting the growth of environmental efficiency.

Industrial structure rationalisation Resource utilisation efficiency is an important criterion to measure whether the industrial structure of a country or region is reasonable. Given other conditions, the higher the resource utilisation efficiency of a specific industry, the more reasonable its industrial structure. At the same time, according to the Pareto optimal criterion of resource allocation, only when the marginal benefits of a resource allocation in various uses are equal, the resource allocation structure achieves Pareto optimality. Therefore, the deviation of the actual factor allocation structure from the equilibrium factor allocation structure can be used to measure the efficiency of resource allocation (degree of rationalisation of the industrial structure). In addition, significant differences in the importance of different industries can be observed, and these differences in importance must be considered when constructing the

rationalisation index of the industrial structure. Drawing on the calculation method of Thiel entropy, $HLH_i = \sum_{j=1}^k \frac{Y_{ij}}{Y} \ln\left(\frac{\frac{L_{ij}}{Y}}{\frac{L}{Y}}\right)$. HLH represents the rationalisation index of the industrial structure; L_{ij} and Y_{ij} represent the labour input and output of industry j in region i , respectively; and L and Y represent the total input and output of industry j in region i , respectively. The larger the HLH , the greater the deviation of the actual industrial structure from the balanced industrial structure, the more unreasonable the industrial structure. Given that the National Bureau of Statistics of China has stopped collecting employment data for each province by three industries since 2011, measuring the rationalisation of the industrial structure directly at the provincial level is impossible. However, considering that the provincial capital city is a centralised reflection of a province's economic and social development, it can be replaced directly by the data of the provincial capital city. The improvement of HLH is conducive to improving the allocation of production resources amongst different industries, improving their allocation efficiency, stimulating the growth of output of SEIs, reducing the cost of the ecological environment and promoting sustainable and rapid growth of environmental efficiency in SEIs. At the same time, the rationalisation of the industrial structure is the basis of the advanced industrial structure. The improvement of the rationalisation of the industrial structure can promote the change of industrial structure to the advanced level, promote the improvement of the scale efficiency of SEIs and promote the growth of environmental efficiency of SEIs.

Proportion of output value of the tertiary industry (service) In contrast to traditional industries, SEIs are technology- and knowledge-intensive industries, and their development requires the support of many high-tech industries (especially high-quality producer services). The improvement of the advanced level of the industrial structure can provide supporting industrial support for the development of SEIs, stimulate scale expansion, provide financial support for future green technology innovation, promote its green technology progress and promote sustained and rapid growth in environmental efficiency.

Government's ability to intervene in the economy (gov) Government purchase is the most direct and effective government intervention in the economy. However, from the perspective of the development status of the financial system, budgetary revenue is an important channel for the government to raise financial funds. Thus, this study directly uses the proportion of government fiscal revenue to GDP to measure the government's economic intervention capability. The larger the ratio, the more resources the government has and the stronger

its ability to intervene in the economy. In addition, given that the problem of environmental pollution is external, a serious market failure occurs in the allocation of environmental resources, making it impossible to achieve the optimal allocation of environmental resources in SEIs simply by relying on market forces and impossible to achieve the best environmental efficiency. As a substitute for the market mechanism, the government can alleviate the problem of market failure to a certain extent, improve the allocation efficiency of environmental property rights of SEIs and promote the sustained and rapid growth of environmental efficiency in SEIs.

Degree of development of the environmental resource trading market (market) The construction of China's direct environmental trading market is relatively lagging, and no systematic statistics on the environmental trading status of environmental resources exists. However, the environmental resource trading market is embedded in the entire market economic system and is an important part of the entire market economic system. The development of the entire market economic system will have an important effect on the development process of the environmental property rights trading market. Therefore, this study uses the market development status of the entire economic system in a specific region as an approximate substitute for the development status of the environmental resource trading market. At the same time, considering that labour is the most active factor in the production process, the marketisation of labour resources is a key part of the marketisation of the factor market system and the core factor that determines the market development process in the factor market system. Therefore, the degree of marketisation of the labour market (the proportion of employees in private and individual enterprises in the total number of employees in urban units) is used directly as a measure of the degree of marketisation of the economic system (that is, the degree of development of the environmental resource trading market). This indicator is expressed directly by the proportion of private enterprises and individual employees in the employment of urban units. The larger the ratio, the larger the proportion of factors allocated through the market mechanism, and the higher the degree of marketisation. A good market environment is conducive to reducing the allocation cost of environmental resources and improving their allocation efficiency, thereby promoting the growth of the environmental efficiency of SEIs. For example, establishing the emission rights trading mechanism can effectively reduce the transaction cost of environmental pollution rights, improve the allocation structure of environmental pollution rights, improve the allocation efficiency of

environmental pollution rights and promote the growth of environmental efficiency in SEIs.

Foreign direct investment The number of foreign direct investment (FDI) registrations is expressed at the end of the year. The effects of FDI on the environmental efficiency of SEIs is reflected in the following two aspects. The first is the technology spillover effect. Compared with domestic capital, the management of FDI is more advanced, and production technology is relatively higher. The entry of FDI enterprises improves the production technology level of domestic SEIs through the technological pushback effect and promotes the continuous and rapid increase in environmental efficiency. The second is the blocking effect of industrial structure transformation. Receiving an industrial transfer from developed countries can effectively shorten the industrialisation process and promote short-term economic growth. However, it contributes to the inertia of the transformation and upgrading of the regional industrial structure, making the host country overly dependent on the industrial transfer of the developed countries instead of actively seeking the transformation and upgrading of the industrial structure according to its development strategy. Thus, it solidifies the original industrial structure of the host country, hinders the transformation of traditional industries to SEIs and hampers the effective development of scale efficiency and the sustained and rapid growth of environmental efficiency. Therefore, the effect of FDI on SEIs is uncertain. If the technological spillover effect is greater than the retardation effect of the industrial structure, then FDI promotes the environmental efficiency growth of SEIs. If the latter is greater than the former, then the entry of FDI inhibits the growth of the environmental efficiency in SEIs.

Ecological construction strength Ecological construction strength (STJS) is expressed directly by the ratio of the area of garden green space in the built-up area to the area of the built-up area. The higher the ratio, the greater the government's ecological construction efforts. It can not only improve the ecological environment in various places directly but also sends a positive signal that the company attaches importance to ecological environmental protection, which reasonably guides the transformation and upgrading of traditional industries, reduces the development resistance of SEIs, decreases the resource and environmental efficiency in the entire social and economic development and promotes the growth of SEIs' environmental efficiency.

Environmental regulation (regulation) Regulation is measured directly by the number of agencies and

personnel of environmental protection agencies. The greater the number and personnel of environmental protection agencies, the stronger the government's ability to intervene in microenvironmental behaviour, the stronger the constraints on the environmental behaviour of microenvironmental power subjects and the stricter the environmental regulations. The improvement of the intensity of environmental regulation can not only directly limit the pollutant discharge behaviour of SEIs, reduce the pollutant emissions of SEIs, weaken the adverse effect on the ecology and promote the growth of environmental efficiency in the development of SEIs but can also effectively guide the flow of production resources between different industries, enhance the ability of SEIs to gather high-quality production resources, enhance their green technology innovation capabilities and promote their green technology innovation and progress. The number of institutions and personnel are two types of indicators of different nature; thus, they cannot be directly calculated. Considering that the entropy method is more objective in constructing weight indicators, the entropy method is used to synthesise the two types. The body process is as follows: Firstly, the indicators are standardised, that is, $y_{ij} = \frac{x_{ij} - \text{Min}x_j}{\text{Max}x_j - \text{Min}x_j} + 0.0001$. x_{ij} represents the original value of the j th indicator of individual i ; $\text{Max}x_j$ and $\text{Min}x_j$ represent the maximum and minimum values of the j th indicator, respectively; and y_{ij} is the standardised value of the j th indicator of individual i . Then, the contribution of individual i to the j th index is calculated, that is, $p_{ij} = \frac{y_{ij}}{\sum_{i=1}^n y_{ij}}$. Secondly, the information entropy is calculated as $e_j = -\frac{1}{\ln k} \sum_{i=1}^n p_{ij} \ln p_{ij}$, where k represents the number of samples. The difference coefficient is calculated, that is, $d_j = 1 - e_j$. Thirdly, the weight coefficient of each indicator is obtained as $w_j = \frac{d_j}{\sum_{j=1}^r d_j}$, where r represents the number of indicators. Finally, the comprehensive score of each individual is calculated, $s_i = \sum_{j=1}^n y_{ij} w_j$.

Fairness and integrity of environmental law enforcement GZLJ is expressed directly by the number of environmental petitions and visiting letters and the number of visiting batches. The larger the number of visits, the lower the fairness and integrity of environmental law enforcement. The lower level of fairness and integrity may reduce the credibility of government environmental regulations, weaken the institutional performance of environmental regulations, increase the pollutant discharge of SEIs, increase the ecological and environmental cost of SEI development reduce the environmental efficiency of SEIs. Similar to environmental regulation, the number of environmental petition letters and batches are also indicators of different nature, and the entropy method is used to synthesise the two.

R&D capital stock This study draws on the method for fixed asset investment index that the perpetual inventory method is used to estimate the initial R&D capital stock. Considering the faster rate of knowledge depreciation, the depreciation rate of R&D capital is set at 0.15. The increase in R&D capital stock is conducive to improving the green technology innovation strength of SEIs, promoting green technology innovation and promoting the growth of environmental efficiency in SEIs.

Data sources and processing

The data required to measure environmental efficiency come from 30 provinces and cities in mainland China (the Tibet Autonomous Region is not considered because of issues with data availability), and the sample interval is 2004–2019. Macro data and data related to SEIs come from *China Statistical Yearbook*, *China High-tech Industry Statistical Yearbook*, *China Environmental Statistical Yearbook*, *China Energy Statistical Yearbook*, relevant provincial SEI development reports, *Provincial (City) Statistical Yearbook* and leadership speeches.

The provincial government's general budget revenue data are from the 'China Macroeconomic Statistical Database'. The total output value of the primary, secondary and tertiary industries and the data of employees in each provincial capital city are obtained. FDI data are from the EPS system 'China Foreign Economic Database'. Data on the number of employees in private enterprises and individuals and the total number of employees in urban areas are from the 'Labour Economic Database' of the EPS system. The per capita income, the number of environmental protection institutions and personnel at the end of the year, the number of environmental petitions and visitors and the data sources of batches of visits are from the EPS system 'Environmental Database'. Data on the green area of the built-up area and the landscaping area are from the 'Urban and Rural Construction Statistical Database' of the EPS system. Fiscal revenue data are from the 'China Finance and Taxation Database' EPS system. The GDP of each province is obtained from the 'China Macroeconomic Database'. Research and experimental development expenditure data are from the 'China Science and Technology Database' EPS system.

In terms of data processing, FDI data are first converted into RMB-denominated amounts at the average exchange rate over the years and then deflated by the fixed asset investment price index, which has been adjusted uniformly to a comparable price level based on 2004. Economic development is deflated by the GDP deflator, which has been adjusted uniformly to the Kobe price level based on 2004. Given that R&D capital has the attributes of consumer and investment goods, the consumer price index and the fixed asset investment price index must be considered

simultaneously when processing its price. On the basis of existing literature, the two weights are set to 0.55 and 0.45.

Regression results

Estimation results of factors influencing environmental efficiency of SEIs

Using the 2004–2019 data of 30 provinces in China (excluding Tibet), the Tobit model explores the influencing factors of the environmental efficiency of SEIs. At the same time, to identify whether regional differences can be found in the effects of the various factors on the environmental efficiency of SEIs, regressions are conducted with samples from the eastern, central and western regions. The specific estimation results are shown in Tables 3 and 4.

Table 3 reports the effect of the various factors on the environmental efficiency of SEIs and the estimated results of regional heterogeneity. Sections (1)–(4) show the influence of various factors on the environmental technical efficiency of SEIs and the estimation results of regional heterogeneity. Columns (5)–(8) show the influence of various factors on the total factor efficiency of the SEI environment and the estimation results of regional heterogeneity. Column (1) shows that Eco, HLH, Service, Gov, STJS, Regulation, GZLJ and RD are significantly related to the environmental technical efficiency of SEIs. HLH, Service, Gov, GZLJ and RD are significantly positive, whereas *STJS* and *Regulation* are significantly negative. In column (5), HLH, Service, Gov, STJS, Regulation and GZLJ are positively correlated with the total factor efficiency of the SEI environment. At this time, Eco and RD have no significant effect on the total factor efficiency of the SEI environment. In addition, the negative effect of environmental regulation on environmental efficiency is considerably evident, and the inhibitory effect is the strongest. The reason may be because in the early stage of environmental regulation, the intensity of environmental regulation is increased to control the pollutant discharge behaviour of SEIs, thereby increasing the production costs of enterprises and resulting in the industry facing great obstacles in the development process and environmental efficiency. However, the behaviour of environmental regulation emphasises improving the sustainable development level of SEIs, and hence, from a long-term perspective, the effects of environmental regulations on environmental efficiency change from negative to positive. Columns (2)–(4) and (6)–(8) show the differences in the degree of influence of various factors on the environmental efficiency of SEIs in different regions. The elasticity coefficient of the economic development level to the environmental technical efficiency in the east and the environmental total factor efficiency in the western region is the largest, thereby indicating that

Table 3 Estimated results of factors influencing environmental efficiency in SEIs

	GT				GM			
	Nationwide	Central	East area	Western	Nationwide	Central	East area	Western
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
<i>Eco</i>	0.032*** (3.52)	0.021 (1.66)	0.031*** (3.17)	0.021 (1.64)	0.041 (1.28)	0.018 (1.49)	0.027* (1.68)	0.051* (1.69)
<i>HLH</i>	0.704*** (3.41)	0.421 (1.61)	0.354 (1.58)	0.732 (1.48)	0.615* (1.79)	0.451 (1.35)	0.046 (1.56)	0.322 (1.23)
<i>Service</i>	0.214*** (3.35)	0.132** (1.98)	0.272*** (2.65)	0.121 (1.64)	0.141** (2.55)	0.220 (1.01)	0.242** (2.16)	0.221 (1.00)
<i>Gov</i>	0.145*** (3.27)	0.151 (1.56)	-0.124 (-1.55)	-0.038 (-1.60)	0.091* (1.74)	0.141 (1.033)	-1.012 (-1.60)	-0.024 (-1.08)
<i>Market</i>	0.103 (1.63)	-0.421 (-1.65)	0.021 (1.48)	0.042 (1.62)	0.089 (1.23)	-0.217 (-1.48)	-0.054 (-1.29)	-0.081 (-1.22)
<i>FDI</i>	0.024 (1.13)	0.112*** (2.64)	-0.021 (-1.64)	0.015** (2.58)	0.017 (1.56)	0.334*** (3.69)	-0.003 (-1.05)	0.031* (1.77)
<i>STJS</i>	-0.647*** (-3.61)	-0.421** (-2.52)	-0.431** (-2.41)	-0.247* (-1.92)	-0.489** (-2.31)	-0.280** (-2.34)	-0.762** (-2.49)	-0.129* (-1.72)
<i>Regulation</i>	-4.754*** (-3.42)	-3.125*** (-2.81)	-2.475** (-2.33)	-4.132 (-1.64)	-4.121** (-2.55)	-3.678 (-1.52)	-3.412* (-1.86)	-2.170 (-0.34)
<i>GZLJ</i>	0.412*** (3.62)	0.245*** (3.10)	0.386** (2.57)	0.248*** (2.76)	0.244** (2.37)	-0.141 (-1.39)	0.212*** (3.39)	-0.161 (-1.39)
<i>RD</i>	0.254*** (3.75)	0.178** (2.45)	0.241** (1.98)	0.178** (2.18)	-0.047** (-2.31)	-0.242*** (-4.88)	-0.124* (-1.96)	-0.224** (-2.33)
<i>Constant</i>	5.412*** (12.42)	6.421*** (11.21)	5.421*** (10.45)	6.478*** (13.45)	4.235*** (10.23)	2.465*** (11.20)	3.423*** (9.62)	4.785*** (12.01)
Observations	404	115	155	134	404	115	155	134
Pseudo R ²	0.345	0.378	0.368	0.346	0.374	0.376	0.281	0.372

The brackets in the table are the estimated coefficient *t*-statistics. **p* < 0.05, ***p* < 0.01, ****p* < 0.001. According to China’s division of the macro-regional economic pattern, the eastern region includes Beijing, Tianjin, Hebei, Liaoning, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong and Hainan. The central region includes Shanxi, Jilin, Heilongjiang, Anhui, Jiangxi, Henan, Hubei and Hunan. The western region includes Inner Mongolia, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Ningxia and Xinjiang

promoting economic development in the west effectively improves the environmental total factor efficiency.

Estimated results of influencing factors of GEC and GTC of SEIs

The results in column (1) of Table 4 show that *Eco*, *Service*, *GZLJ* and *RD* are significantly positive for the technological improvement of SEIs. Their elastic coefficients are all significantly positive at 1% confidence level, with elastic coefficients of 0.029, 0.175, 0.372 and 0.427, respectively, indicating that for every one percentage point increase in *Eco*, *Service*, *GZLJ* and *RD*, the technological improvement of SEIs increases by 0.029%, 0.175%, 0.372% and 0.427%, respectively. By contrast, *FDI*, *Regulation* and *Gov* have a significant negative effect on technological improvement of SEIs. When *FDI* is relatively high, receiving an industrial transfer from developed countries can shorten the industrialisation process and

promote short-term economic growth. It also contributes to regional industrial structure transformation and upgrading inertia, which make the host country overly dependent on industrial transfer from developed countries. Suppose it does not actively seek to transform and upgrade the industrial structure according to its development strategy, it solidifies the original industrial structure of the host country and hinders the transformation of traditional industries to SEIs. Ultimately, technological improvement of SEIs will be inhibited, resulting in a negative elasticity coefficient between the level of *FDI* and technological improvement in SEIs. This result may be because the government interferes too much in emerging industries, which is not conducive to the enthusiasm of emerging industries. Moreover, excessive government intervention increases the production cost of emerging industries, and emerging industries cannot promptly make technological improvements due to lack of funds. The results in columns (2)–(4) of Table 4 show the differences in the

Table 4 Estimated results of factors influencing GEC improvement and GTC of SEIs

	GTC				GEC			
	Nationwide	Central	East area	Western	Nationwide	Central	East area	Western
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
<i>Eco</i>	0.029*** (2.76)	0.018 (1.56)	0.024** (2.17)	0.051*** (2.65)	0.032** (2.44)	0.025* (1.82)	0.018* (1.95)	0.035 (1.57)
<i>HLH</i>	−0.304 (−1.61)	0.103 (1.42)	−0.171 (−1.54)	−1.132 (−1.38)	1.213** (2.29)	0.982** (2.35)	1.624*** (2.85)	0.236*** (3.23)
<i>Service</i>	0.175*** (3.15)	0.141* (1.94)	0.072 (1.65)	0.146*** (2.69)	0.086* (1.76)	−0.024 (−1.44)	0.143*** (2.78)	0.085 (1.56)
<i>Gov</i>	−1.175** (−2.27)	−1.951 (−1.54)	−0.971 (−1.45)	−1.038 (−1.63)	−2.362*** (−3.42)	−2.64** (−2.55)	−0.663 (−1.04)	−2.125 (−1.53)
<i>Market</i>	0.203 (1.52)	−0.531 (−1.54)	0.254** (2.42)	0.005 (1.32)	0.168** (2.18)	−0.085 (−1.21)	0.078 (1.64)	0.178 (1.39)
<i>FDI</i>	−0.342*** (−3.13)	0.142 (1.64)	−0.044 (−1.64)	0.005 (1.58)	−0.217 (−1.54)	0.323* (1.83)	−0.018 (−1.58)	0.375 (1.56)
<i>STJS</i>	0.661 (1.51)	0.516 (1.52)	−0.157 (−1.41)	−1.246* (−1.87)	−0.356 (−1.53)	−0.442 (−1.29)	−0.178 (−1.58)	−1.123* (−1.87)
<i>Regulation</i>	−2.623** (−2.42)	−1.025* (−1.81)	−2.414** (−2.13)	−2.170 (−1.55)	−2.42 (−1.55)	−3.742 (−1.58)	−1.687 (−1.52)	−1.843* (−1.93)
<i>GZLJ</i>	0.372*** (3.42)	0.189** (2.08)	0.186** (2.49)	0.148* (1.76)	0.346*** (3.44)	0.421** (2.43)	0.141* (1.86)	0.146 (1.55)
<i>RD</i>	0.247*** (3.75)	0.198** (2.57)	0.124 (1.32)	0.092 (0.18)	−0.026* (−1.75)	−0.021 (−1.38)	−0.042* (−1.82)	0.012 (1.24)
<i>Constant</i>	6.410*** (11.32)	5.275*** (9.35)	4.278*** (8.95)	3.215*** (13.21)	5.240*** (9.45)	2.275*** (9.78)	5.274*** (12.20)	5.012*** (13.01)
Observations	404	115	155	134	404	115	155	134
Pseudo R^2	0.384	0.387	0.382	0.290	0.282	0.278	0.384	0.291

The brackets in the table are the estimated coefficient t-statistics. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. According to China's division of the macro-regional economic pattern, the eastern region includes Beijing, Tianjin, Hebei, Liaoning, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong and Hainan. The central region includes Shanxi, Jilin, Heilongjiang, Anhui, Jiangxi, Henan, Hubei and Hunan. The western region includes Inner Mongolia, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Ningxia and Xinjiang

degree of influence of various factors on the technological improvement of SEIs in different regions. In terms of economic development level, the economic level of the eastern region is the highest, and its industrial technology improvement has reached a certain level, whereas the economic level of the central and western regions is relatively backward. Therefore, the improvement of economic level has a greater marginal value of technological improvement of its emerging industries. In addition, the proportion of Service, GZLJ and RD are undeniably important variables for promoting technological improvement in SEIs. By contrast, Regulation and STJS are the variables that inhibit technological improvement in SEIs.

The results in column (5) of Table 4 show that Eco, HLH, Service, Market and GZLJ have a significant positive correlation with the efficiency improvement of SEIs, and their elastic coefficients are 0.032, 1.213, 0.086, 0.186 and 0.346, respectively. Therefore, we believe that the level of industrial structure is an important factor in

promoting the efficiency improvement of SEIs. The higher the rationalisation level of the industrial structure, the higher the resource utilisation efficiency determined by the industrial structure, the Pareto optimal resource allocation efficiency and the most remarkable improvement effect on industrial efficiency. The government's ability to intervene in the economy often causes damage to the economic interests of enterprises and affects the production enthusiasm of enterprises, thereby inhibiting the improvement of enterprise efficiency. Enterprises with high R&D capital stock are not beneficial to enterprise development. It makes enterprises comfortable with the status quo, making it difficult to obtain optimal use of resources, and adversely affects the efficient development of firms.

The results in columns (6)–(8) of Table 4 show the different influences of each factor on the efficiency improvement of SEIs in different regions. From the perspective of the industrial structure's rationalisation level, the eastern region's industrial rationalisation level has the most

remarkable improvement in the efficiency of SEIs, and the western region is the weakest. Industrial development has reached a certain level, and many industries face development bottlenecks because of the relatively high level of economic development in the eastern region. Improving the rationalisation level of the industrial structure can effectively help the eastern region break through the bottleneck and achieve a breakthrough in improving industrial efficiency. In addition to rationalising the industrial structure, the fairness and integrity of law enforcement are important factors to ensure the efficiency improvement of emerging industries, which positively affect the efficiency improvement of SEIs in the central, eastern and western regions.

Analysis of the dynamic cooperation mechanism of the environmental efficiency of SEIs

Definition of dynamic subject

Identifying the power subjects of SEIs is the premise of analysing the relationship between the power subjects of environmental efficiency of SEIs. The key to improving the environmental efficiency of SEIs lies in increasing the expected output through technological innovation, focusing on environmental protection and reducing undesired output. Improving expected output requires technological innovation in SEIs, and reducing undesired output requires focusing on environmental protection and reducing pollutant emissions in industrial development. Therefore, the definition of the main power body of the environmental efficiency of SEIs includes the power mechanism and the evolution of the ecosystem.

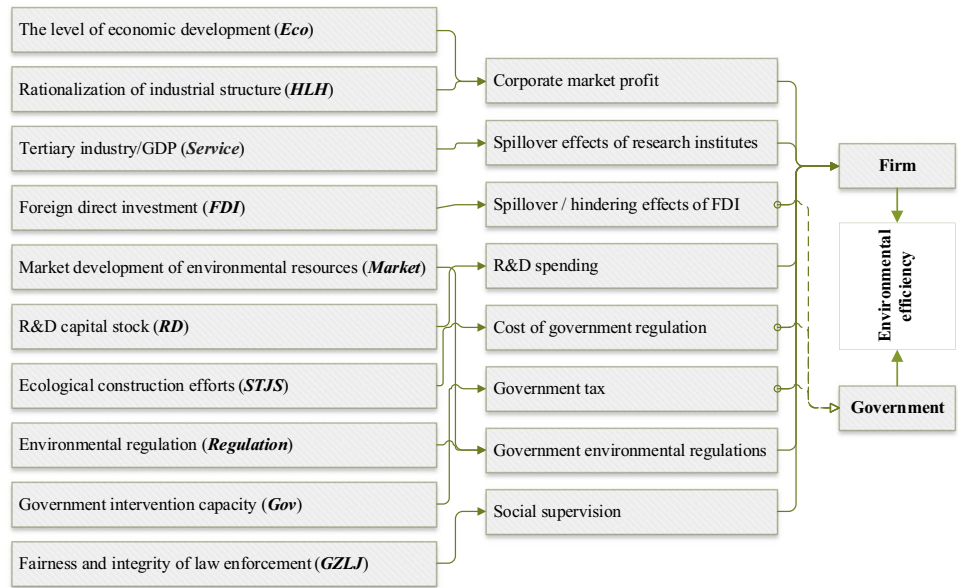
In terms of power mechanism, Pavan et al. (2014) believe that government needs, government competition and government motivation generate power, whereas market gravity, policy thrust and learning effects amongst enterprises are power development mechanisms. Athey and Segal (2013) construct an efficient, budget-balanced, Bayesian incentive-compatible mechanism for general dynamic environments with quasilinear returns. In this environment, agents observe private information and make decisions over countably many periods. Bergemann and Välimäki (2019) describe the dynamics of social optimality (or efficiency) and further consider a model for time-varying groups of agents. Forbes and Kirsch (2011) believe the development of SEIs is inseparable from the top-level design at the national level and that regional governments should also combine local characteristics to develop leading industries and promote the independent

development of multiple entities. They further posit that the formation process of the independent technological innovation capability of SEIs is a dynamic and complex system. The formation of independent technological innovation capability is inseparable from the coordinated development of the three main bodies: firm, government and scientific research institutes.

The dynamic subject is studied from the perspective of game theory. Etzkowitz and Leydesdorff (1995) propose the triple helix theory for the first time, explaining the interaction amongst the government, enterprises and universities (research institutions) in the era of knowledge economy. Triple helix theory believes that the main body of innovation is no longer limited to enterprises. Governments, firms and universities (scientific research institutions), as relatively equal partners, are the main bodies of innovation. The increasing ‘overlap’ amongst the three is the core innovation unit. Triple helix theory emphasises that through a certain institutional design and structural arrangement between the ‘official, industry and academia’, resource sharing and information communication amongst the three should be strengthened to achieve the maximum efficiency and effectiveness of innovative resources. Veronica and Thomas (2007) analyse the collaborative innovation system from the two dimensions of integration and interaction and believe that collaborative innovation is a multiparty communication–coordination–cooperation–synergy process. Chen et al. (2021) believe that the collaborative innovation activities of manufacturing industry clusters need to realise the collaborative interaction of multidimensional innovation subjects of enterprises, governments, universities, scientific research institutions and intermediaries to promote the development of industrial innovation jointly. Moreover, the dynamic evolution process of collaborative innovation between governments, enterprises and universities is analysed through the establishment of an evolutionary game model with manufacturing enterprises and scientific research institutes as the main body. Yang et al. (2021) use evolutionary game theory to analyse the game behaviour amongst the government, enterprises and universities (research institutions) under bounded rationality and discuss the evolutionary path, stable equilibrium strategy and its influencing factors.

As shown in the above literature, the environmental efficiency of SEIs is jointly affected by the government, enterprises, scientific research institutions, universities, FDI, financial institutions, intermediary organisations and customers. The innovation system of SEIs is constantly evolving with the continuous adjustment of subject behaviour. The government embodies national interests, has strong guidance and can promote the sound development of SEIs.

Fig. 1 The influence indicators of environmental efficiency in SEIs



Enterprises are an integral part of SEIs and producers of market economy sources. Therefore, the development of SEIs is inseparable from enterprises, and because SEIs are technology- and knowledge-intensive industries, the technical support provided by scientific research institutes (including scientific research institutions and universities) and FDI is important for SEIs. Technological innovation is crucial. With the development of social civilisation, social supervisors (including consumers, public intermediaries) play an increasingly important role in economic development, and their public opinion supervision has an important effect on the behavioural decision making of enterprises and governments. To this end, this study categorises the driving forces that affect the environmental efficiency of SEIs into three categories: government, firm and social supervision.

Analysis of impact indicators

This study selects the 10 factors in the previous section to analyse the impact indicators and determine in detail how these factors directly affect the behavioural decisions of enterprises, governments and social supervisors and environmental efficiency. To this end, this study classifies these 10 influencing factors into eight impact indicators, namely, corporate market profits, spillover effects of scientific research institutes, spillover effects/blocking effects of FDI, government supervision costs, government taxation, potential benefits from government environmental regulation and social oversight. By affecting the benefits and costs of enterprises, government departments and social supervisors, these indicators affect the

behavioural decisions of enterprises, governments and social supervisors and the environmental efficiency of SEIs, as shown in Fig. 1.

With the corporate market profit, the operating profit obtained by a strategic emerging enterprise is the difference between operating income and production cost.

With the spillover/hindering effects of FDI, the technology spillover effect brought by FDI can bring technological progress and introduce environmental protection technology to the host country's enterprises to generate economies of scale, improve resource utilisation efficiency and reduce production costs. However, if FDI is not well guided and managed, it brings technical obstacles to enterprises, causing enterprises to develop in the direction of high consumption and high pollution and increasing production costs. The cooperation between scientific research institutes and enterprises to carry out green technology innovation is part of the introduction of local technology. The technology spillover effect brought by it can also accelerate the agglomeration of SEIs, improve environmental efficiency and increase income.

With the R&D spending, green innovative production in SEIs inevitably increase the cost of R&D expenditures of enterprises, thereby affecting the total profits of enterprise production. Therefore, as a for-profit organisation that pursues maximising revenue, R&D expenditure has become an important reference for enterprise production decisions.

With the costs of government regulation/nonregulation, the government is a defender of the country's overall benefits. If the government chooses environmental supervision, then it pays for the cost of supervision. If it chooses to ignore the traditional behaviour of enterprises, it may need

to remediate the environment. The success of the two strategies has become an important factor affecting the government's decision-making.

With the government tax, taxation is the main source of the government's economy. Only certain economic benefits can support the government's support and guidance for social and economic development.

With the government environmental regulation, this study divides the government's environmental regulation into government subsidy and rewards for the green innovation behaviour of the enterprise and the government's fine and punishment for the noninnovative production of the enterprise. Government support is the main factor in mobilising the enthusiasm of enterprises because of the economic externalities of the innovative green production of enterprises. At the same time, the government, as the maintainer of the overall social benefits, has the responsibility of supervising and imposing certain fines on the behaviour of enterprises that do not innovate and waste resources and pollution, which can not only regulate the production behaviour of enterprises but also play a role in creating a good ecological environment.

In social supervision, social supervisors include every individual (the public) living in the social environment, green environmental protection organisations for environmental protection, intermediary organisations that reduce transaction costs through information transmission and news media that benefit from public opinion dissemination. The participation of social supervisors in supervision can bring huge potential gains and losses to enterprises and the government and thus can also affect the decision-making of enterprises and governments.

Mechanism of the main power body to improve the environmental efficiency of SEIs

Mechanism of government's action on the environmental efficiency of SEIs

Government regulation is the main driving force for improving the environmental efficiency of SEIs. Government behaviour affecting the environmental efficiency of SEIs is reflected mainly in the encouragement policies, mandatory restraint policies and the pursuit of comprehensive interests. The government provides financial compensation to developers through measures, such as tax incentives, financial subsidies, land incentives and R&D investment subsidies because of the negative externalities of the environmental efficiency economy. The government also adopts active education funding subsidies for scientific research institutes to encourage them to participate actively in the green innovation cooperation of enterprises

and speed up the transformation and upgrading of enterprises. Moreover, by formulating industry standards and punitive measures and improving supporting laws and regulations to ensure implementation, the government puts pressure on enterprise decision-making and guides innovative green production. The optimisation of social, environmental, economic and other comprehensive benefits is the ultimate pursuit of the government.

Mechanism of enterprises' action on environmental efficiency of SEIs

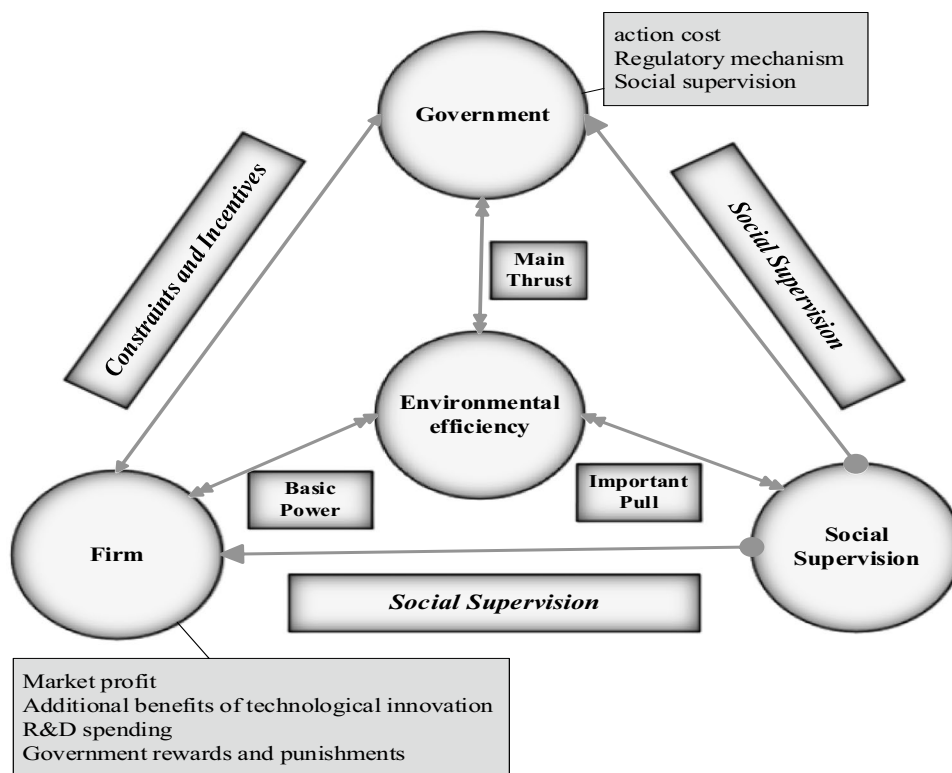
The green innovation of enterprises is the basic driving force for improving the environmental efficiency of SEIs. Enterprises actively conducting structural green transformation and upgrading can greatly improve the environmental efficiency of SEIs. The above analysis of influencing factors shows that the motives for enterprises to carry out green innovation to promote the improvement of environmental efficiency are divided into two categories. The first is the internal driving force of enterprises. An enterprise is a profit-oriented organisation that pursues the maximisation of profits and the realisation of its own goals. Enterprises take the initiative to transform and upgrade the green structure to meet the social development trend and pursue their long-term interests. At the same time, the participation and cooperation of scientific research institutions bring economic spillover effects to the green transformation of enterprises and greatly reduce green costs. The second is the external driving force, that is, the role of public opinion supervised by social supervisors (including the public, news media, third-party organisations) and the constraints and incentives of relevant government management departments.

Mechanism of social supervisors on the environmental efficiency of SEIs

The public opinion supervision power of social supervisors has a positive effect on improving environmental efficiency. Social supervisors exert public opinion pressure by supervising the government and enterprises and influencing the decision-making of the government and enterprises. Under the pressure of social supervision, the government, as the embodiment of the interests of the public, takes regulatory actions under the pressure of maintaining social civilisation and harmony and the acquisition of corporate interests is inseparable from the support of the public.

The above analysis shows that the behaviour of firms, governments and social supervisors jointly affect the environmental efficiency of SEIs, as shown in Fig. 2.

Fig. 2 The mechanism of the action of the main power body on the environmental efficiency in SEIs



Evolutionary game of power-subject cooperation

Improving the environmental efficiency of SEIs is a dynamic game process of cooperation amongst various power subjects. Given that the internal personality as the main body has bounded rationality, in the innovation game, they constantly adjust their participation strategy in accordance with the strategies of other subjects and their adaptability in the cluster to improve their interests. For the convenience of research, this study takes the enterprises in the industry as one type of power subject and the government as another type of power subject under the supervision of social supervisors. An evolutionary game model with SEI enterprises and the government as the main body is established, and the dynamic evolution cooperation process is analysed.

Basic assumptions and establishment of the model

This study is based on the evolutionary game method to analyse the conflict of interests and optimal choices of firms and governments. The following assumptions are made:

Firstly, in improving environmental efficiency, enterprises may actively fulfil their social responsibilities; increase investments in human, material and financial resources; introduce innovative technologies for green and innovative products; and improve environmental efficiency. It may also be limited to short-term interests and may choose not to carry out green innovation production and follow the previous

production technology and only consider the maximisation of interests and leave the ecological environment to be destroyed,¹ that is, the strategic space of the enterprise is {*greeninnovation*, *noinnovation*}. Government departments may formulate information policies, implement administrative accountability mechanisms and strictly supervise the production behaviour of enterprises. It may also choose not to regulate because of the difficulty in implementing regulations or the high cost of regulations. The government's strategy space is {*supervision*, *nosupervision*}. Social supervisors have the right to choose whether to participate in supervision, and the probability of choosing supervision is α ($0 \leq \alpha \leq 1$).

Secondly, in accordance with the abovementioned impact indicators of environmental efficiency of SEIs and in combination with the actual costs, benefits and losses of enterprises and governments under different strategic combinations, the relevant parameters and their meanings are set, as shown in Table 5.

¹ Under the environmental supervision of the government, FDI will fulfil its environmental protection responsibilities, and cooperation with enterprises will bring technology spillover effects to enterprises. In the absence of government supervision, FDI will not fulfil its environmental protection responsibilities, which may cause the host country's enterprises to evolve in the direction of high energy consumption and high pollution, which will bring technological spillover effects to enterprises and produce technological blocking effects. The green production of enterprises participating in scientific research institutes will only bring about technological spillover effects.

Table 5 Setting and meaning of game subject parameters

Parameter	Variable definitions
1 C_g	Cost of environmental supervision by the government (supervision cost+ecological construction cost)
2 T	Government tax
3 C_r	Sewage charges (fines) are charged by the government for noninnovative production when the government conducts environmental supervision
4 R_r	When the government conducts environmental supervision, the government provides bonus subsidies for enterprises to carry out green innovative production
6 R_o	Potential social benefits of government environmental regulation (e.g., increased credibility)
7 C_o	Reputational damage of the government’s failure to conduct environmental regulation
8 R_e	Benefits of enterprises not engaging in innovative production
9 C_e	Cost of enterprises not innovating production
10 C_s	Cost of technology research and development for firms
11 C_n	Cost of environmental remediation that the government needs to pay when enterprises do not carry out innovative production
12 R_p	Technology spillover effects of FDI
13 C_p	Technological blocking effect of FDI
14 R_l	Technological spillover effects of scientific research institutes participating in green innovation of enterprises
15 R_q	Social support (including potential benefits) for green innovative production of enterprises
16 C_q	Losses under public opinion supervision when the enterprise does not carry out innovative production
17 α	Probability of social surveillance

Table 6 Game strategy portfolio and income statement

		Government	
		Supervision	No supervision
Firm	Green innovation	$R_e - C_e + R_p + R_l - C_s + R_r + \alpha * R_q$; $T - C_g - R_r + \alpha * R_o$;	$R_e - C_e + R_p + R_l - C_p - C_s + \alpha * R_q$; $T - \alpha * C_o$;
	No innovation	$R_e - C_e - C_r - \alpha * C_q$; $T - C_g + C_r + \alpha * R_o - C_n$;	$R_e - C_e - \alpha * C_q$; $T - \alpha * C_o - C_n$;

Thirdly, according to the above assumptions and the dependence of the strategies of the companies and the government, the evolutionary model of the company and the government is established by using the game benefit matrix, as shown in Table 6.

Fourthly, we assume that in the initial state, the probability of an enterprise choosing the ‘green innovation’ production strategy is x , and the probability of choosing the ‘no innovation’ strategy is $1 - x$. The probability that the government chooses the ‘ecological regulation’ strategy is y , and the probability that the government chooses the ‘non-regulation’ strategy is $1 - y$, where $0 \leq x \leq 1, 0 \leq y \leq 1$.

Copy dynamic equation analysis

According to the payment matrix of both sides of the game, the expected utility of the enterprise implementing the green innovation strategy is as follows:

$$U_{c1} = y * (R_e - C_e + R_p + R_r - C_s + R_r + \alpha * R_q) + (1 - y) * (R_e - C_e + R_p + R_r - C_s + R_r + \alpha * R_q) \tag{8}$$

The expected utility of enterprises not implementing green innovation strategies is as follows:

$$U_{c2} = y * (R_e - C_e - C_r - \alpha * R_q) + (1 - y) * (R_e - C_e - \alpha * R_q) \tag{9}$$

The average expected utility of a firm is as follows:

$$\bar{U}_c = x * U_{c1} + (1 - x) * U_{c2} \tag{10}$$

Therefore, the dynamic replication equation of the enterprise strategy can be obtained as.

$$f(x) = \frac{d(x)}{dt} = x(1 - x)[y * (C_r + C_p + R_r) + \alpha * (C_q + R_q) + R_p + R_l - C_s - C_p] \tag{11}$$

According to the payment matrix of both sides of the game, the government chooses the expected utility of the ecological supervision strategy as follows:

$$U_{g1} = x * (T - C_g - R_c + \alpha * R_o) + (1 - x) * (T - C_g + C_r + \alpha * R_o - C_n) \quad (12)$$

The expected utility of the government choosing not to regulate the strategy is as follows:

$$U_{g2} = x * (T - \alpha * C_o) + (1 - x) * (T - \alpha * C_o - C_n) \quad (13)$$

The average expected utility of government is as follows:

$$\bar{U}_g = x * U_{g1} + (1 - x) * U_{g2} \quad (14)$$

A replicating dynamic equation of the government's strategy can be obtained as.

$$f(y) = \frac{d(y)}{d(t)} = y(1 - y)[-x * (C_r + R_r) + \alpha * (C_o + R_o) + C_r - C_g] \quad (15)$$

Taking the derivation of the replication dynamic equation $f(x)$ of the enterprise of Formula (4.4), we can obtain the following:

$$\frac{d(x)}{d(x)} = (1 - 2x)[y * (C_r + C_p + R_r) + \alpha * (C_q + R_q) + R_p + R_l - C_s - C_p] \quad (16)$$

From the stability of replicating the dynamic equation, that is, the ordinary differential equation, x as a stable strategy should satisfy $f(x) = 0$, and $df(x)/d(x) < 0$.

(I) If $y = \frac{C_s + C_p - \alpha * (C_q + R_q) - R_p - R_l}{C_r + C_p + R_r}$, then $f(x) = 0$. Under this condition, the strategic choice of the enterprise does not change because of the change of time, and the enterprise chooses any probability to provide green innovative production in a stable state.

(II) If $y \neq \frac{C_s + C_p - \alpha * (C_q + R_q) - R_p - R_l}{C_r + C_p + R_r}$, let $f(x) = 0$, then we can obtain two balance points of $x = 0$ and $x = 1$. At this time, the balance point should be discussed on a case-by-case basis.

(1) When $R_p + R_l - C_s - C_p > 0$, $\frac{df(x)}{d(x)}|_{x=0} > 0$, $\frac{df(x)}{d(x)}|_{x=1} < 0$, $x = 1$ is the evolutionary stability point, which means it is without the influence of third-party supervision from the society. If the additional profit obtained by enterprises in green innovation is positive when the government does not supervise, enterprises decisively choose green innovation production. (2) When $R_p + R_l - C_s - C_p < 0$, two cases exist:

$y * (C_r + C_p + R_r) + \alpha * (C_q + R_q) + R_p + R_l - C_s - C_p > 0$, which satisfies $(1 - y) * C_p + y * R_r + \alpha * R_q + R_p + R_l - C_s > (y * C_r + \alpha * C_q)$, $\frac{df(x)}{d(x)}|_{x=0} > 0$, $\frac{df(x)}{d(x)}|_{x=1} < 0$, $x = 1$ is the evolutionary stability point;

$y * (C_r + C_p + R_r) + \alpha * (C_q + R_q) + R_p + R_l - C_s - C_p < 0$, which satisfies $(1 - y) * C_p + y * R_r + \alpha * R_q + R_p + R_l - C_s < -(y * C_r + \alpha * C_q)$, $\frac{df(x)}{d(x)}|_{x=0} < 0$, $\frac{df(x)}{d(x)}|_{x=1} > 0$, $x = 0$ is the evolutionary stability point. This

result shows that when the government does not supervise, the additional profit obtained by the enterprise when conducting green innovation is negative, whereas when the additional profit obtained by the enterprise conducting green innovation is greater than the loss value of the enterprise not conducting innovative production, the enterprise still chooses green innovation. When the additional profit obtained by the enterprise in green innovation is less than the negative value of the loss value when the enterprise does not innovate production, the enterprise decisively chooses not to innovate production.

We derive the replication dynamic equation $f(y)$ of the government of Formula (4.8) and obtain the following:

$$\frac{d(y)}{d(y)} = (1 - 2y)[-x * (C_r + R_r) + \alpha * (C_o + R_o) + C_r - C_g] \quad (17)$$

As a stable strategy, y should satisfy $f(y) = 0$ and $\frac{df(y)}{d(y)}$.

(I) If $x = \frac{\alpha * (C_o + R_o) + C_r - C_g}{C_r + R_r}$, then we have $f(y) = 0$. Under this condition, the government's strategic choice does not change because of time change, and the government chooses any probability for the ecology to be stable.

(II) If $x \neq \frac{\alpha * (C_o + R_o) + C_r - C_g}{C_r + R_r}$, let $f(y) = 0$, then two equilibrium points, $y = 0$ and $y = 1$, can be obtained. The balance point should be discussed on a case-by-case basis. (1) When $\alpha * (C_o + R_o) + C_r - C_g < 0$, the variant is $T + \alpha * R_o + C_r - C_g - C_n < T - \alpha * C_o + C_r \frac{df(y)}{d(y)}|_{y=0} < 0$ is obtained, $\frac{df(y)}{d(y)}|_{y=1} > 0$, $y = 0$ is the evolutionary stable point.

This result shows that when firms conduct nongreen innovative production and government supervision costs less than the cost of no ecological supervision, the government chooses an ecological supervision strategy. (2) When $\alpha * (C_o + R_o) + C_r - C_g > 0$, two types of situations emerge. If $\alpha * (C_o + R_o) + C_r - C_g > x * (C_r + R_r) > 0$, that is, $T + \alpha * R_o + (1 - x) * C_r - x * R_r - C_g - C_n > T - \alpha * C_o + C_n$, $\frac{df(y)}{d(y)}|_{y=0} > 0$, $\frac{df(y)}{d(y)}|_{y=1} < 0$, $T + \alpha * R_o + (1 - x) * C_r - x * R_r - C_g - C_n < T - \alpha * C_o - C_n$, $\frac{df(y)}{d(y)}|_{y=0} < 0$, $\frac{df(y)}{d(y)}|_{y=1} > 0$, $y = 0$ is the evolutionary stable point. This result indicates that the government chooses ecological regulation with the expected benefits when the government ecologically regulates the enterprises that are greater than those not regulating. When the government's expected benefits when eco-regulating enterprises are smaller than those not regulated, the government chooses not to eco-regulate due to the high cost of regulation consideration.

Evolutionary stability analysis

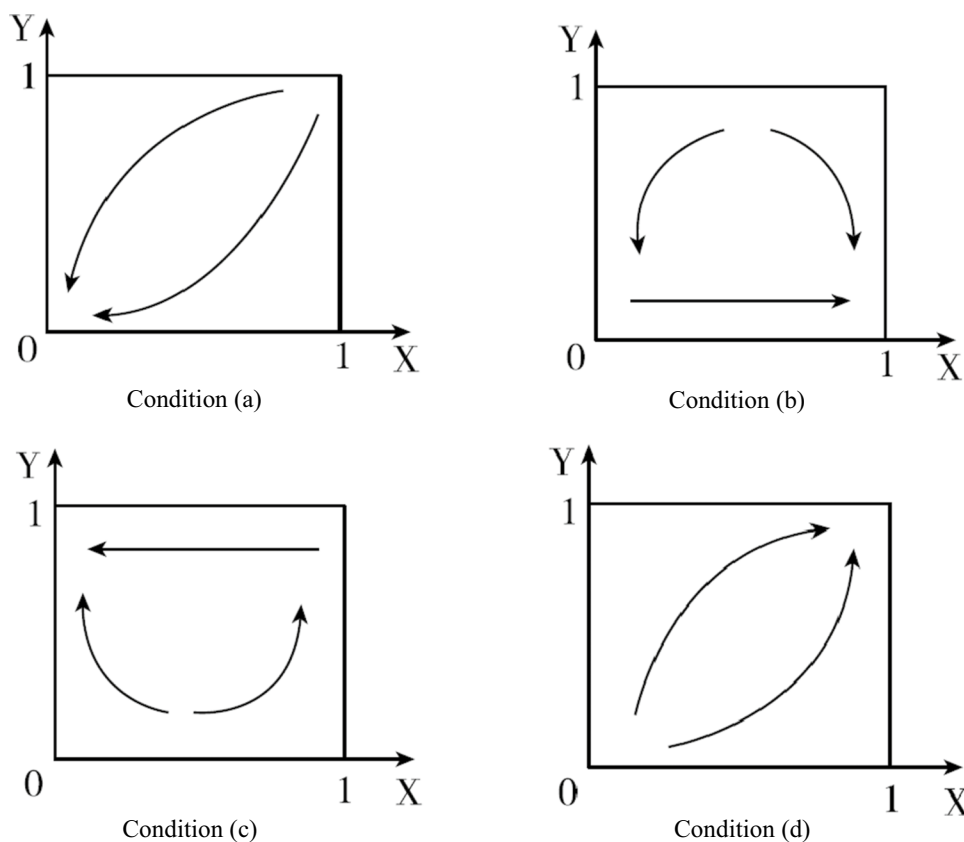
Let $f(x) = dx/dt = 0$ in Formula (4.4), $f(y) = \frac{dy}{dt} = 0$ in Formula (4.8). The plane $M = \{(x, y) | 0 \leq x, y \leq 1\}$ has five local equilibria of the game system, which are $(0, 0)$, $(1, 0)$, $(0, 1)$, $(1, 1)$ and $(x, y) = ((\frac{C_r - C_g + \alpha * C_o + \alpha * R_o}{C_r + R_r}), -(R_l - C_s - C_p + R_p - C_q * \alpha + R_q * \alpha) / (C_p + C_r + R_r))$. The stability analysis of the local equilibrium

Table 7 Local stability analysis of the firm–government evolutionary game system

Equilibrium point	$det(J)$	$tr(J)$	Condition	Stability conditions	Results
(0, 0)	+	-	a	$\alpha * C_q < C_s + C_p - \alpha * R_q - R_l - R_p;$ $\alpha * C_o < C_g - C_r - \alpha * R_o$	ESS
(1, 0)	+	-	b	$\alpha * C_q > C_s + C_p - \alpha * R_q - R_l - R_p;$ $\alpha * C_o < C_g + C_r - \alpha * R_o$	ESS
(0, 1)	+	-	c	$\alpha * C_q + C_r < C_s + C_p - \alpha * R_q - R_l - R_p - R_r$ ESS ; $\alpha * C_o > C_g + C_r - \alpha * R_o$	ESS
(1, 1)	+	-	d	$\alpha * C_q + C_r > C_s + C_p - \alpha * R_q - R_l - R_p - R_r$ ESS ; $\alpha * C_o > C_g + C_r - \alpha * R_o$	ESS
(x, y)	0	0			Saddle point

ESS stands for evolutionary stable strategy

Fig. 3 Evolution phase diagram of conditions a–d



point can be obtained by analysing the local stability of the Jacobi matrix of the system. Taking partial derivatives of $f(x)$ and $f(y)$ concerning x and y , respectively, we have the following:

$$\begin{bmatrix} \frac{\partial f(x)}{\partial(x)} & \frac{\partial f(x)}{\partial(y)} \\ \frac{\partial f(y)}{\partial(x)} & \frac{\partial f(y)}{\partial(y)} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \tag{18}$$

where

$$a_{11} = -(x - 1) * (R_l - C_s - C_p + R_p + y * (C_p + C_r + R_r) + (C_q + R_q) * \alpha) - x * (R_l - C_s - C_p + R_p + y * (C_p + C_r + R_r) + (C_q + R_q) * \alpha) \tag{19}$$

$$a_{12} = -x * (x - 1) * (C_p + C_r + R_r) \tag{20}$$

$$a_{21} = y * (y - 1) * (C_r + R_r) \tag{21}$$

$$a_{22} = (y-1) * (C_g - C_r - \alpha * (C_o + R_o)) + y * (C_g - C_r - \alpha * (C_o + R_o)) + x * (C_r + R_r) \quad (22)$$

If the trace of the Jacobian matrix is $tr(J) < 0$, the determinant $det(J) > 0$, then the equilibrium point of the replicated dynamic equation is the local stability point. Therefore, the above five equilibrium points can be analysed, and the conclusions are shown in Table 7.

According to Table 6, we can plot the dynamic evolution trend of the strategy choice of both enterprises and government, as shown in Fig. 3. In the absence of government regulations, the value of loss (the difference between additional cost and additional benefit) for firms choosing to produce green innovations is greater than the value of loss for firms not producing innovations under social supervision and the cost of government regulation of firms not to innovate production is greater than the value of damage to the reputation of the government not to regulate under social supervision. The final stable equilibrium state of the two-party game is $x = 0$ and $y = 0$, that is, the enterprise does not innovate production, and the government does not supervise. In the absence of government supervision, the loss value (the difference between the additional cost and the additional benefit) of enterprises choosing green innovative production is smaller than the loss value of enterprises that do not innovate production under social supervision. The cost of government regulation of green production of enterprises is greater than the reputation damage value of the government's nonregulation under social supervision. The final stable equilibrium state of the two-party game is $x = 1$, $y = 0$, that is, the enterprise conducts green innovative production, and the government does not supervise it. When an enterprise chooses green innovative production, the loss value (difference between additional cost and additional benefit) is greater than the loss value of noninnovative production under social supervision, and the cost of government regulation of noninnovative production of enterprises is less than the reputation damage value of the government's nonregulation under social supervision. The final stable equilibrium state of the two-party game is $x = 0$, $y = 1$, that is, the enterprise conducts noninnovative production, and the government conducts supervision. The loss value (difference between additional cost and additional benefit) of enterprises choosing green innovative production is less than the loss value of enterprises not innovating production under social supervision, and the cost of government regulation on green production of enterprises is less than the reputation damage value of the government's nonregulation under social supervision. The final stable equilibrium state of the two-party game is $x = 1$, $y = 1$, that is, the enterprise conducts green

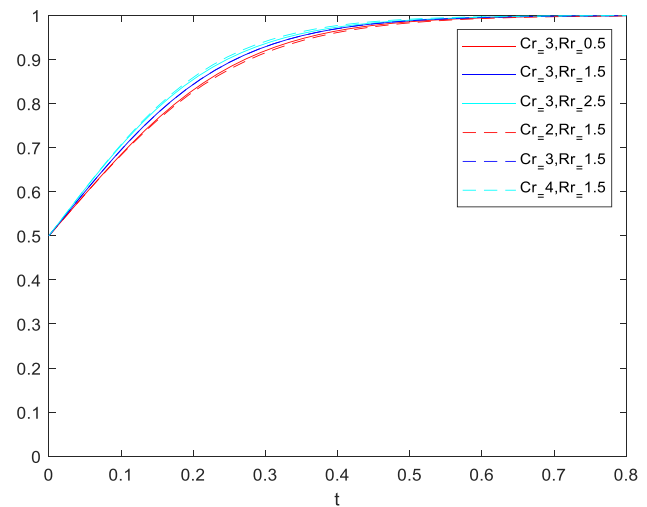


Fig. 4 The impact of government rewards and punishments on corporate behaviour

innovative production, and the government conducts supervision.

In summary, $\{innovation, regulation\}$, $\{innovation, no\ regulation\}$, $\{no\ innovation, regulation\}$ and $\{no\ innovation, no\ regulation\}$ may be the evolution and stability strategies of the system. The state $\{innovation, supervision\}$ is the optimal equilibrium state. Thus, to avoid other situations effectively and make the system evolve to an optimal state, this study numerically simulates the dynamic evolution process between strategic emerging companies and government behaviour whilst changing the initial variables of the system.

Numerical experiments and simulations

We refer to existing studies (Yang et al. 2021; Chen et al. 2021). The model sets the initial evolution time to 0 and the evolution time to 0–5 years (up to 5 years). The initial values of the parameters in the game model are set as follows: $R_e=10$, $C_e=4$, $R_p=4$, $R_l=2.5$, $C_s=3$, $R_r=2$, $R_q=3$, $C_g=2$, $T=20\%*(10-4)=1.2$, $C_g=5$, $R_r=2$, $R_o=5$, $C_o=4$, $C_p=2.5$, $C_n=3$, $C_r=3$ and $\alpha=0.6$. The initial ratio of corporate and government strategies is $X_0 = Y_0 = 0.5$. We focus on government subsidies and fines on strategic emerging enterprises and the government, social third-party participation probability on enterprises and the government and technological spillovers from FDI and scientific research institutions on corporate decision making. These discussions provide a basis for promoting enterprises and the government to adopt the strategy of $\{innovation, supervision\}$.

The effect of government rewards and punishments on corporate behaviour In Fig. 4, the vertical axis is the

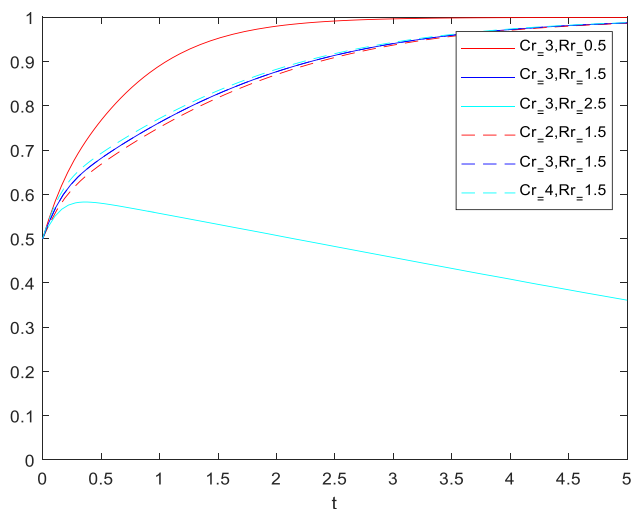


Fig. 5 The impact of government rewards and punishments on government behaviour

probability of firms choosing green innovative production strategies, the horizontal axis represents time and the solid line represents when the government and enterprises maintain the initial probability state ($X_0 = Y_0 = 0.5$). When other parameters remain unchanged, the relative change of the subsidy value R_r given by the government to enterprises for green innovative production affects the selection strategy of enterprises in the system. R_r gradually increases from 0.5, and a simulation is performed for each change of R_r by 1. The three equilibrium lines in the figure indicates that with the increase in subsidy value R_r , the enterprises tend to balance green innovative production strategies faster and shorter, and the time becomes shorter. It shows that increasing the number of government subsidies can stimulate the enthusiasm of enterprises for green innovation and guide enterprises to choose green innovation production strategies. The dotted line in Fig. 4 represents the equilibrium diagram of the strategic choice of the enterprise when other conditions remain unchanged, and the pollutant discharge fee C_r charged by the government supervision on the traditional production behaviour of the enterprise is assigned as 2, 3 and 4 in turn. The three equilibrium lines indicate that with the increase in the penalty value C_r , the enterprises tend to balance green innovative production strategies faster and shorter. However, compared with increasing the reward value of green innovative production of enterprises, increasing the reward value of green innovative production of enterprises and increasing the penalty value of traditional production had a better effect on promoting green innovative production behaviour enterprises.

The effect of government rewards and punishments on government behaviour The government’s reward

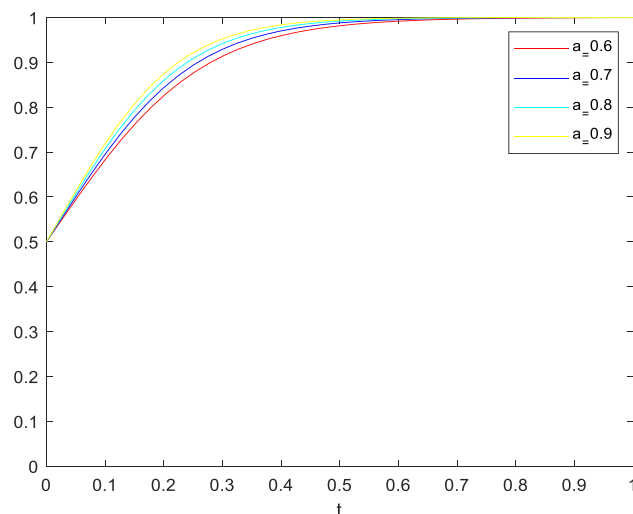


Fig. 6 The impact of third-party surveillance on corporate behaviour

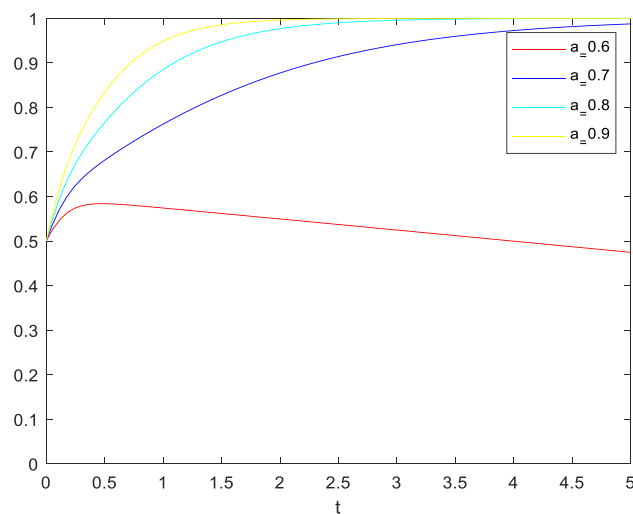


Fig. 7 The impact of third-party surveillance on government behaviour

and punishment for corporate behaviour are the cost of government environmental supervision. The solid line in Fig. 5 indicates that the government and enterprises maintain the initial probability state ($X_0 = Y_0 = 0.5$). When other parameters remain unchanged, under government supervision, the relative change of the subsidy value R_r of enterprises’ green innovation production behaviour affects the government’s choice strategy in the system. The three equilibrium lines in the figure indicate that R_r gradually increases from 0.5, and the government tend to choose environmental regulation. As R_r increases ($R_r=2.5$), the probability that the government chooses environmental regulation tends to zero mainly because the benefit of government regulation

is $T - C_g - R_r + \alpha * R_o$. If other parameters remain unchanged, increasing the reward amount substantially reduces the government's profits. If no other benefits make up for the cost of supervision, local governments will not be motivated enough to motivate their behaviour. After long-term development, government regulation costs exceed the government's ability (system boundary) and eventually evolve into nonregulation. The dotted line in Fig. 5 shows the effect of the relative change of the pollutant discharge fee C_r , charged on the enterprise's noninnovative production behaviour on the government's choice strategy when other conditions remain unchanged under the government's environmental supervision. The government's collection of sewage charges from noninnovative production by enterprises is a benefit of the government, which can offset the cost of government environmental supervision. Therefore, when C_r ($C_r=2, C_r=3, v=4$) increases gradually, the government's environmental supervision strategy tends to approach one faster, as shown by the three dotted lines in the figure.

The effect of social third-party supervision on business and government strategies The social third party is one of the members of the social environment. When enterprises and the government work together to protect the environment, a good social environment benefits from them. At this time, third parties in society have high willingness to participate in ecological supervision. Therefore, this study starts from 0.6 for the value of α . Figures 6 and 7 show the numerical simulation results of the corporate and government strategies when the probability of the social third-party choosing to supervise changes under the premise of other conditions remains unchanged. The results in Fig. 6 show that when the probability of a third party in the society choosing to supervise increases gradually, enterprises tend to choose green innovative production faster, and the time to reach an equilibrium state is shortened. This result is due mainly to the potential gains and losses generated behind the supervision of third-party public opinion in society. When an enterprise chooses green innovative production, the higher the probability that a third party in the society chooses to participate in supervision, the more potential benefits the enterprise can obtain, including the corporate image, which consumers recognise; national fiscal and taxation, land support policies and bank loan policies favour green production enterprises. In addition, the loss of social third-party participation in the supervision of the traditional production of enterprises cannot be underestimated, especially when the news media participates in reporting. The loss increases exponentially. When companies weigh the effects of social third-party supervision, they see that the development prospects of green innovative production become more active and tend to choose green innovative production. Figure 7 shows that when the probability of the

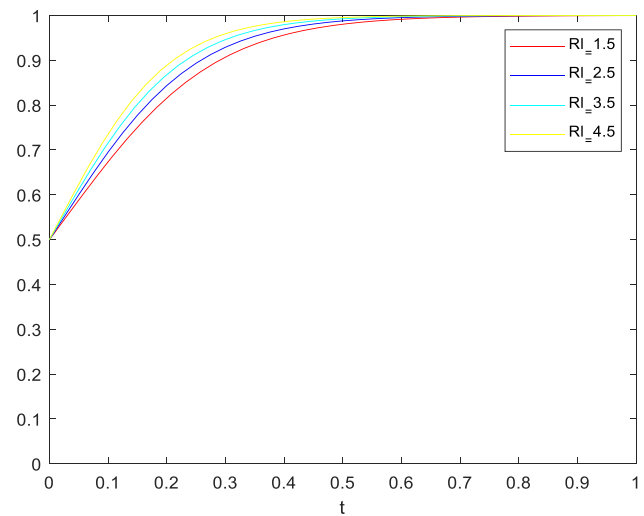


Fig. 8 The impact of scientific research institutions on corporate behaviour

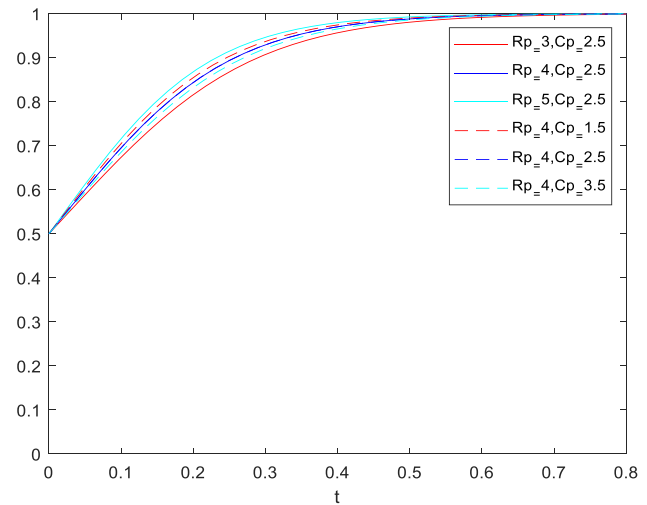


Fig. 9 The impact of FDI on corporate behaviour

social third party choosing the supervision probability is only 0.6 and the government chooses ecological supervision with a benefit utility less than the supervision cost, choosing ecological supervision tends to approach zero. With the increase in α ($\alpha=0.8, 0.9$), the probability that the government chooses ecological regulation finally converges to 1. The result is consistent with the analysis of the effects of social supervision on corporate strategies above. The public opinion pressure of third parties participating in the supervision of government behaviour brings potential gains and losses to the government.

The effect of technology spillovers from FDI/research institutions on corporate strategies FDI and scientific research institutions are two different means of green innovation for

enterprises. The international enterprises represented by FDI have high and new technologies and perfect environmental protection technologies. FDI can bring technological progress to the host country's enterprises and introduce environmental protection technologies through technology spillover effects. However, if FDI is not well guided and managed, it causes technical obstacles to enterprises, making enterprises develop in the direction of high consumption and high pollution. The cooperation between scientific research institutions and enterprises to carry out green technology innovation belongs to the introduction of local technology, and its technology spillover effect can accelerate the agglomeration of SEIs and improve environmental efficiency. Figures 8 and 9 respectively show the effects of the technological spillover effects of scientific research institutions' participation and FDI in green innovation on corporate strategies when other conditions remain unchanged. The results in Fig. 8 show that with the greater technological spillover effect caused by the participation of scientific research institutions in the green innovative production of enterprises, enterprises tend to adopt green innovative production faster when they expect the benefits of green innovative production will be greatly improved. The solid line part in Fig. 9 shows that the technological spillover effect brought by FDI to enterprises can also positively affect enterprises' green innovation production strategy. However, the dotted line also reflects that the technical hindrance of FDI prolongs the time for enterprises to tend to green innovative production. Therefore, as a double-edged sword, RDI needs to fulfil its environmental protection responsibilities under the supervision of the government to bring the best results to the green innovation transformation of Chinese enterprises.

Conclusions and implications

This study takes the provincial panel data from 2004 to 2019 as its research object and uses SBM directional distance function and the GML index to measure China's SEIs. We investigate the influencing factors of the environmental efficiency of SEIs based on the panel Tobit model and find that rationalisation of the industrial structure, proportion of the tertiary industry, government's ability to intervene in the economy, and fairness and integrity of environmental law enforcement improve environmental efficiency in SEIs. Conversely, intensity of ecological construction and environmental regulation hampers environmental efficiency in SEIs. Moreover, the evolutionary game model and numerical simulation analyse the cooperation mechanism between the power agents. Specifically, social supervision and government regulation, which work together in influencing the environmental efficiency of SEIs. {innovation, supervision} is the optimal equilibrium

state of the game. In the absence of government regulation, foreign direct investment (FDI) slows down the speed of firms tending to the equilibrium state of green innovation. In addition, the potential gain and loss of social supervision on corporate behaviour is an important factor affecting government behaviour decision making. In this regard, governments prefer punishment tools in environmental regulation, therefore influencing noninnovative firms in SEIs.

Theoretical implication

This study draws some important implication as follows: Firstly, we develop an effective measurement tool of environmental efficiency. By using the SBM directional distance function and the GML index to measure the environmental efficiency of China's SEIs, the results indicated that under environmental constraints, the environmental technical efficiency, environmental total factor efficiency, efficiency improvement and technological improvement of provincial SEIs are relatively fast, indicating a fluctuating upward trend with differences between provinces, but the overall environmental efficiency level is low.

Secondly, we comprehensively examine the factors affecting the environmental efficiency of SEIs, thereby providing important empirical evidence for guiding the development of SEIs. Based on exploring the influencing factors of environmental efficiency, this study firstly uses the evolutionary game model to analyse how to establish an effective cooperation mechanism amongst various power agents to promote the improvement of environmental efficiency jointly, and further use numerical simulation to analyze the specific impact of each parameter on the behavioural decision making of power agents. This study constructing the panel Tobit model of the influencing factors of the industrial environmental efficiency of SEIs, HLH, Service, Gov and GZLJ are found to have a significant positive correlation with the environmental efficiency of SEIs, and STJS, Regulation inhibits the improvement of environmental efficiency of SEIs. A regional heterogeneity in the effects of the various factors on the environmental efficiency of SEIs can be observed. After decomposing the total factor efficiency of the environment, the level of industrial rationalisation is found to have the most remarkable effect on technological improvement in the eastern region, and the western region is the weakest. The fairness and integrity of law enforcement are important factors in ensuring efficiency.

Thirdly, we discuss the influencing factors of environmental efficiency on the basis of an evolutionary game model. Specially, we analyse the effective cooperation mechanism of government, firm and social

supervision in promoting the improvement of environmental efficiency jointly and the use of numerical simulation to analyse the specific influence of each parameter on the behaviour decision of the diversified actors. Specifically, through the evolutionary game analysis of the cooperation of dynamic subjects, behavioural strategies of game decision-making subjects have been found to depend often on the behavioural decisions of the other party and that social supervision also affects the behavioural strategies of the government and enterprises. $\{innovation, regulation\}$ is the optimal equilibrium state of the game. The numerical simulation results of the optimal equilibrium state show that increasing the probability of participation in social supervision increases the government's reward or punishment for corporate behaviour. The technological spill-over effects of FDI and scientific research institutes have a positive effect on corporate green innovation behaviour. In the absence of government supervision, the technological blocking effect of FDI on the green innovation of enterprises slows down the speed of enterprises, tending to the equilibrium state of green innovation. The potential gains and losses of social supervision to corporate behaviour is an important factor affecting government behaviour decision-making. The government tends to choose to increase the punishment for noninnovative behaviour of enterprises due to the consideration of supervision costs, which play a role in environmental regulation.

Practical implication

Based on the above conclusions, this study proposes that environmental efficiency of SEIs can be improved further in four aspects. Firstly, the government can strengthen its environmental regulations, including strengthening the publicity of green enterprises and the public's green behaviour and improving the reward and punishment and supervision mechanisms for corporate behaviour. Secondly, it should give full play to social supervision, actively supervise government and enterprise behaviour and urge enterprises and government behaviour to improve through public opinion supervision. Thirdly, enterprises should reasonably introduce foreign investment, use their technology spillover effects to implement technological reforms and enhance their independent innovation capabilities to avoid the blocking effect caused by technology introduction. Fourthly, the government's cooperative governance mechanism, enterprises and social supervisors and the benign interaction of the three should be improved to improve the environmental efficiency of SEIs effectively. In addition, it can further expand the enterprise innovation system, optimise the industrial

structure, increase government purchases, innovate financing support, promote the construction of professional talent teams, improve the environmental resource trading market and develop SEIs according to local conditions.

Author contribution Shulin Xu designed this study, participated in all phases and analyzed the data; Qingzhen Zhu contributed analysis tools and wrote the complete paper. Zhen Yang contributed analysis tools and revised the paper. All authors read and approved the final manuscript.

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Data availability The datasets used and/or analyzed during the current study are available from the China Statistical Yearbook, China High-tech Industry Statistical Yearbook, China Environmental Statistical Yearbook, China Energy Statistical Yearbook and relevant provincial strategic emerging industry development reports, provincial (city) statistical yearbooks and leaders' speeches.

Declarations

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Consent for publication Not applicable.

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