Heliyon 10 (2024) e26508

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Environmental regulation, land use efficiency and industrial structure upgrading: Test analysis based on spatial durbin model and threshold effect

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A R T I C L E I N F O

Keywords:
Environmental regulation
Land use efficiency
Industrial structure upgrading
Threshold effect
China's Yangtze River Economic Belt

A B S T R A C T

Environmental regulation promotes industrial structure change and regional economic transformation through land use adjustment, which gets a new way to explore the path of reforming traditional industrialization and urbanization. Based on the panel data of 128 prefecture-level cities in China 's Yangtze River Economic Belt from 2000 to 2020, this paper uses the spatial Dubin model to analyze the impact of environmental regulation and land use efficiency on the upgrading of industrial structure, and sets the panel threshold model to examine the impact of environmental regulation on the upgrading of industrial structure by affecting land use efficiency. The results show that formal environmental regulation has a significant positive spatial effect on the rationalization and upgrading of industrial structure, which are 0.1734 and 0.2854 respectively. Informal environmental regulation has a negative spillover effect on neighboring provinces but not significant. Heterogeneous environmental regulation has obvious "double threshold effect" on industrial upgrading by affecting land use efficiency. When the threshold of environmental regulation intensity is 0.0315–0.0886, environmental regulation still inhibits land use efficiency and industrial structure upgrading. When the threshold value is greater than 0.0886, environmental regulation has a positive impact on land use efficiency but not significant. With the intensity of environmental regulation from weak to strong, it will produce a double threshold effect of "strong inhibition-weak inhibition-interaction promotion" on the upgrading of manufacturing structure through the adjustment of land use efficiency.

1. Introduction

Regional development is still accompanied by crises. It is an eternal topic in global regional development[1] search for a path of transformation in the change of external environment. With the global and regional flow and transfer of industrialization and urbanization, more and more countries begin to pay attention to the consequences of environmental regulation on land use and industrial transformation[2]. Environmental regulation is a social system formulated by government departments to carry out environmental governance by specific discharge standards ordischarge fees[3], it affects economic growth, local government competition[4], and green economic development[5]. In the start-up period and acceleration period of urbanization, the local government's "growth first"

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https://doi.org/10.1016/j.heliyon.2024.e26508
Received 6 September 2023; Received in revised form 4 February 2024; Accepted 14 February 2024
Available online 6 March 2024

governing philosophy and extensive development model have brought serious environmental pollution problems[6]. Environmental regulation guides industrial space adjustment and structural change by regulating land use efficiency, and promotes regional economicand social stage-by-stage leapfrogging[7].

Environmental regulation has traditionally been taken into account as a necessary tool to alleviate the environmental pressure caused by inappropriate growth patterns and their land use. Many governments have implemented a series of environmental regulatory policies [8,9]. They intervene in the upgrading of industrial structure by changing industrial development interventions such as management concepts, environmental management, competitiveness, and the potential for financial performance[10,11], as well as the demand for open space[12]. Environmental regulation will change the type of regional investment enterprises through the scale and layout of land marketization, and then regulate the upgrading of industrial structure. However, previous studies have proposed the dual impact of environmental regulation[13], believing that it increases the cost of environmental protection facilities and squeezes out some corporate investment[14] , but in the context of the global emphasis on green innovation and development[15], this paper finds that previous studies have neglected this important change in the regional industrial structure by regulating the land use efficiency of environmental regulation, and there are few studies that investigate the joint role of environmental regulation and land use efficiency in the industrial structure, while exploring the impact of environmental regulation and land use efficiency on the regional industrial structure, which has an enlightening effect on the region's future adjustment policies, industrial transformation and green innovation and development.

Since the beginning of the 1980 s, China 's major cities began to undertake a large number of international industrial transfer[16], relying on extensive, " environment for growth " development mode to bring rapid economic development, per capita GDP level has reached the forefront of the world[17]. However, in the past, the choice of extensive economic growth methods such as investment resource-intensive[18] and labor-intensive fields has culminated in the low-end locking of the value chain[19]. Ignoring the rationalization and advancement of factor allocation and environmental costs, it not only leads to a certain degree of overcapacity, industrial structure convergence, low production efficiency and other resource factor mismatch problems [20], but also brings serious industrial pollution, air pollution, solid wastewater pollution and other environmental diseases, which seriously threaten regional sustainable development[21]. However, we find fewer studies that explore the deeper issues that lead to these questions - does environmental regulation have an impact on regional industrial allocation? Does land use efficiency significantly affect regional resource allocation and lead to industrial transfer? We find that these questions have not been clearly reflected in previous studies, and the quantitative interpretation of environmental regulation and land use efficiency through spatial econometric analyses is the key to answering the question of green innovation in this era. Therefore, this paper takes China 's Yangtze River Economic Belt (CYREB) as a case to quantitatively evaluate the impact of environmental regulation (ER) on land use efficiency (LUE) and industrial structure upgrading (ISU). This paper tries to explore the endogenous effects among the three by using the spatial Durbin model, and at the same time, adopts the threshold model to explore the depth of industrial structure changes caused by heterogeneous environmental regulation to regulate the efficiency of land use, so that the corresponding optimization strategies can be proposed after these quantitative analyses to supplement the gaps in the current research field.

The main structure of this paper consists of six parts. The introduction part explains the main research background, research significance and puts forward the research questions of this paper: heterogeneous ER is used to influence LUE on ISU; in the review section, the current research results are compared, and the threshold effect of ER, ER and LUE, as well as the mechanism of action between ER, LUE and ISU are discussed. The third part mainly explains the selection and optimization of methods, the selection of variables and the processing of data from the research data and methods. The fourth part is mainly to carry out empirical analysis, which visually illustrates the comprehensive level of rationalized industrial structure (RIS), advanced industrial structure (AIS), ER and LUE in the CYREB, further analyzes the spatial effect of industrial structure upgrading and rationalization, and then discusses the threshold of environmental regulation for industrial structure. The fifth part compares and analyzes the similarities and differences between this paper and the existing research, and explains some defects of this paper and future research directions. Finally, according to the above analysis and discussion, the conclusion of this paper is expounded.

2. Literature review and theoretical framework

2.1. The threshold effect of environmental regulation

Environmental regulations in relation to public goods exhibit obvious externalities, and optimal environmental policies have a phased nature. According to the perspective of classical economics, environmental protection increases business costs and reduces the competitiveness of economic development. Based on this, Porter and Van der Linde proposed the “Porter Hypothesis”, which states that appropriate ER standards can encourage technological innovation in businesses, thereby enhancing competitiveness [22]. Environmental economics suggests that excessively stringent ER can crowd out productive investments, inevitably reducing production efficiency and industrial competitiveness [23]. Conversely, insufficient environmental regulations make it difficult to incentivize business investment in technological innovation [24]. Environmental psychology emphasizes the relationship between the society and the environment [25]. It also confirms the close interdependence between social development and the environment from the side. Most scholars agree with the “Porter Hypothesis” and the existence of a threshold effect between environmental regulations and production efficiency [26–28]. In other words, the role of environmental regulations in promoting both high economic growth and quality urbanization has a threshold effect, displaying a nonlinear or inverted “U"-shaped relationship [29]. When crossing a certain turning point, the effect shifts between promotion and inhibition[30]. Only with rational environmental regulations can the threshold effect be overcome, facilitating the transformation and upgrading of industrial structures, and achieving a win-win situation for ER and development of the economy.

However, ER can be divided into informal environmental regulation (IER) and formal environmental regulation (FER) [31], which are increasingly prominent in promoting the upgrading of industrial structures [32]. New structural environmental economics suggests that different ER tools need to be implemented at different stages of economic growth. Generally, heterogeneous ER play a significant role in the early stages of economic development and middle to high-income stages. In the early stages, industrial structures are mostly labor-intensive or land-intensive, and market exchanges have not yet entered a formal track. It is more challenging to incorporate environmental externalities into the market system. Therefore, government intervention with relatively low intervention costs and easy implementation is preferred. At this stage, command-type ER tools would be more effective. Currently, the intensity of ER in China is still on the left side of the "U"-shaped curve, and ER may inhibit the transformation and ISU[33].

2.2. Environmental regulation and land use efficiency

The transformation of land resources from quantity-driven to efficiency-driven is the main theme of modern urban land use [34]. ER and LUE have long been a focus of research ([35]; [36]; [37,38]). LUE aims to maximize economic output while utilizing land to its fullest extent [39]. Distinctive forms of environmental regulations also have heterogeneity in their effects on LUE. Zhang et al. argue that both IER and FER can improve LUE, and only when the intensity of ER exceeds 0.8612, the regulations can enhance urban LUE [40]. The impact of environmental regulations on LUE can be understood from two perspectives: "mechanism cost effect" and "Porter effect." The mechanism cost effect refers to the governance costs brought about by environmental regulations, such as environmental protection taxes, pollution control equipment, and production process updates, which force companies to face strong financing constraints. The Porter effect refers to the effective implementation of environmental regulations that cut off the transmission path of "resource curse," making it advantageous for companies to internalize costs, incentivize innovation, and achieve reduced ecological governance costs and increased product profits [41].

China's land policy has undergone a process from "directed supply" to "market-oriented supply." Currently, it has formed a policy system that integrates planning, supply, incentives, and regulation to pursue the maximization of comprehensive land use benefits. However, in the actual implementation process, there are still problems such as the unreasonable policy structure, inconsistent policy goals, and inadequate policy implementation, which result in insufficient policy effects and hinder the overall improvement in LUE [42]. With the advancement of urbanization and industrialization in China, the Chinese economy is at a critical period of transitioning from high-speed growth to high-quality development. The green economic model driven by innovation instead of factor inputs has become an important characteristic of regional transformation, and the effects of environmental regulations in the land use process are receiving increasing attention. Whether from the perspective of China's economic structural reform and resource and environmental constraints or from the complexity of the external environment and the trend of global industrial revolution, improving LUE is the core driving force for promoting high-quality economic development [43]. In this critical period, the contradiction between environmental protection and urban LUE has become a serious issue that hinders China's socio-economic development. It is essential to dialectically examine the regional heterogeneity and spatial differences in the impact of environmental regulations on LUE from the perspectives of both the "environmental regulation inhibition theory" and the "environmental regulation control theory".

2.3. Environmental regulation and industrial structure upgrading

The upgrading of industrial structure is a key path to coordinate economic development with high quality and environmental protection. The relationship between environmental regulations and industrial structural upgrading is complex and typically exhibits a U-shaped pattern, rather than a simple linear relationship. When ER is weak, it inhibits the upgrading of industrial structure. Only when it exceeds a certain threshold does it promote the upgrading of industrial structure [44]. ER mainly affects the overall industrial structure by influencing the "two transformations" of the industrial structure. Through the formulation of environmental regulations, the government, in one respect, increases the cost of pollution control and production for enterprises, resulting in frictional and structural unemployment, leading to social cost compensation and loss of social welfare [45,46]. In another respect, it encourages enterprises to engage in environmentally friendly technological innovation under the existing market environment, promoting the adjustment and upgrading of industrial structure. At the enterprise level, this includes promoting employment and wage levels in industries with high technology and low energy consumption, thereby enhancing the level of human capital in the industry [47].

The impact of ER on the continuous development of regions can be seen in the phenomenon of "pollution havens"[48]. Since the 1980s, scholars have found that as environmental standards in developed countries continue to tighten, pollution-intensive industries in Western Europe, North America, Japan, and other developed countries have flowed to developing countries, indicating that stricter ER policies have a dis-incentive effect on pollution-intensive enterprises, and these enterprises prefer regions with lower environmental regulation intensity [49]. This is mainly because regions with greater development pressure are more willing to relax environmental regulations, and in the absence of sufficient factor endowments and financial guarantees, they tend to choose complementary competition strategies with developed regions, adopting a remedial governance strategy of "pollution first, treatment later"[50].

This occurrence is even more significant in China, which implements economic performance assessment policies. The internal financial pressure of local governments leads to biased attitudes towards capital taxes, productive expenditures, and environmental protection tax and fee expenditures. They tend to relax ER and introduce pollution-intensive enterprises for policy and resource allocation [51]. On the other hand, the verticalization of ER policies by the central government also stimulates local industrial technological innovation, industrial structure adjustment, and optimization of resource allocation. With the reform of China's ecological civilization system [52], the implementation of classified governance strategies for main functional zones, and the green performance assessment system, local governments are encouraged to implement stricter ER while weakening their willingness to attract foreign pollution-intensive enterprises. Instead, they choose recyclable industries that match their local resource endowments. This has led to phenomena such as "race to the bottom," "competitive upgrading," "competition championship," and "free-riding," [53]inhibiting the enthusiasm of local governments for environmental protection, distorting the supply structure of public goods, reducing environmental quality, and exacerbating regional protectionism in the process of regional economic development and tax collection. It impedes the free flow of factors between regions, creating market segmentation and resource mismatches.

2.4. Environmental regulation, land use efficiency and industrial structure upgrading

Advancing the upgrading of industrial structure is a crucial pathway for achieving high-quality economic development in a country. However, industrial development is the core source and macro foundation of LUE. The implementation intensity of environmental regulations directly affects industrial types, thereby influencing industrial structural adjustment through the intermediate effects of "compliance cost effect" or "innovation compensation effect" on enterprises [54–56]. This, in turn, affects land resource allocation and efficiency development [57–60]. The environmental structure and its changes, transformation, and operation are endogenous to the production structure determined by factor endowment structure[61]. They exert backward pressure on the production structure and influence the technological structure[62]. Industrial structural transformation is accompanied by dynamic transfer of factors, knowledge, and technological innovation[63,64].

Environmental regulations, by affecting LUE, promote industrial upgrading and exhibit significant nonlinear relation[65]. The transformation of industrial structure changes the relative importance of the three sectors of industry, thereby affecting the allocation of production factors such as resources, capital, and labor among industry sectors, leading to corresponding adjustments in land space and changes in efficiency[66]. For the traditional industrialization industrialization of "development only", with the continuous development of the region, when the LUE reaches the t' threshold, the LUE gradually declines to t ", leading to the imbalance of regional industrial structure and the continuous decline of urban development. On the other hand, for the sustainable development path, the initial stage may have lower land resource utilization efficiency. However, when the LUE reaches the t value, the ER will be added. Although the LUE will be weakened in the short-term development, when the g value weakens, the regional adaptability to ER will be enhanced, and the regional LUE rapidly grows to g' is the same as the traditional route efficiency, as development progresses and through the implementation of regional environmental regulations and rational land resource utilization, a "win-win" result can be achieved through a non-linear adaptive stage, promoting regional industrial structural upgrading and high-quality development (Fig. 1).

3. Study area, methods and data sources

3.1. China's Yangtze River Economic Belt

CYREB covers 11 provinces and cities including Shanghai, Jiangsu, Zhejiang, and Anhui. It spans the eastern, central, and western regions of China, with an area of approximately 2.0523 million square kilometers, accounting for 21.4% of the country's total (Fig. 2). In 2022, the permanent population of the CYREB accounted for 43.1% of the national total, with an urbanization rate of 55.5%. The region's GDP accounted for 46.5% of the national total, and its population and economic scale occupy a significant portion of the country.

In terms of industrial structure, the 11 provinces and cities in the CYREB have further optimized their industrial structures. From 2001 to 2020, the average ratio of the three industries has shifted from 8.1:40.6:51.1 to 7.8:38.8:53.5, with a decrease in the share of

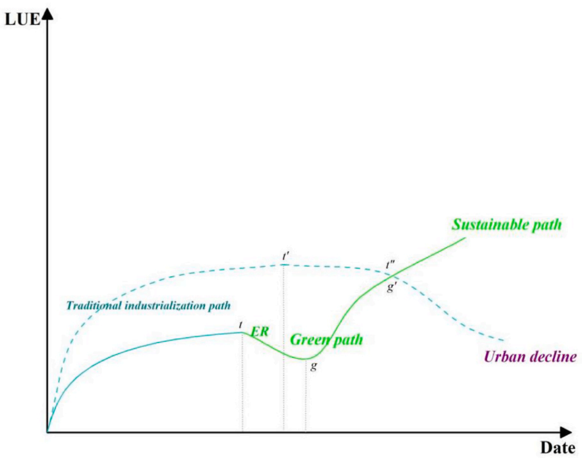

Fig. 1. Environmental regulation, land use efficiency and sustainable development relationship.

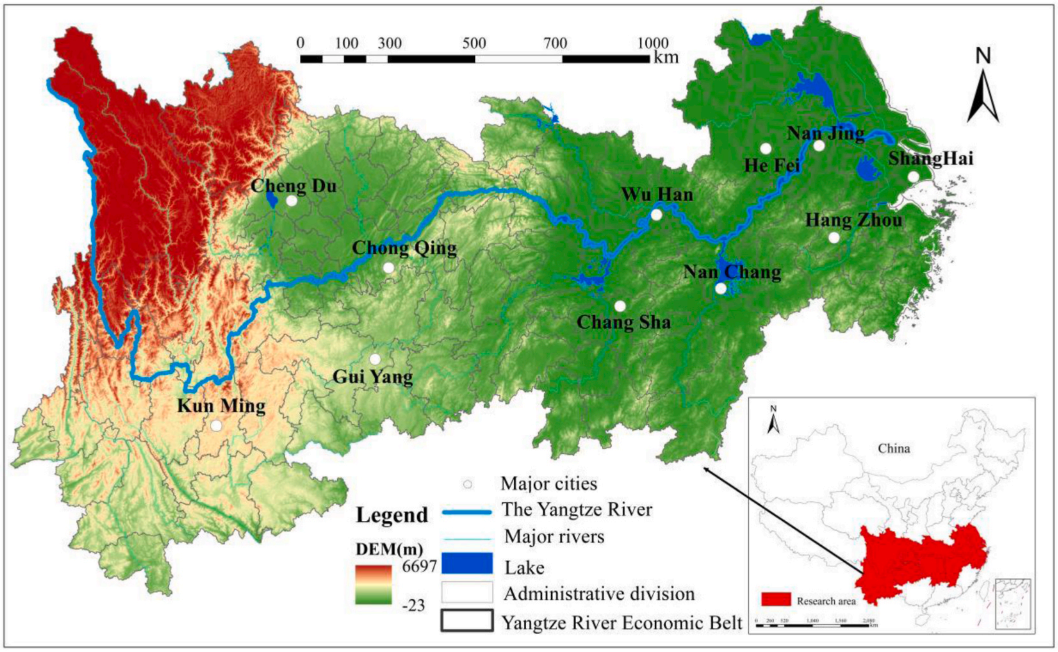

Fig. 2. Basic overview chart of the Yangtze River Economic Belt.

the primary and secondary industries and an increase of 2.4 percentage points in the share of the tertiary industry. In terms of regional distribution, except for an increase in the share of the secondary industry in Zhejiang and the share of the primary industry in Hunan, the share of the primary and secondary industries has decreased in other regions, while the share of the tertiaryindustry has increased in all 11 provinces and cities.

3.2. Establishment of the spatial measurement model

Investigating the effects of LUE and environmental regulations on industrial structural upgrading necessitates considering spatial factors. Spatial econometric models capture the complex spatial relationships among variables within observed units. Specifically, spatial lag models, spatial error models, and spatial Durbin models are commonly used. The spatial Durbin model combines the advantages of spatial error and spatial lag models[67], allowing for the examination of both the impact of other regions on the dependent variable and spatial spillover effects within the study area. Additionally, considering the dynamic persistence of environmental policies [68], the "time inertia" resulting from this characteristic should also be incorporated into the research scope. Therefore, this study identifies ER and LUE as the main explanatory variables while controlling for other factors influencing ISU. Furthermore, taking the logarithm of both sides of the equation is employed to address heteroscedasticity[69] and multicollinearity issues[70]. The model is set as follows:

$$ln\ ISU_{it} = \alpha_1 ln\ FER_{it} + \alpha_2 ln\ IER_{it} + \alpha_3 ln\ LUE_{it} + \alpha_4 X_{it} + \epsilon_{it} \tag{1}$$

In the formula : ISU_{it} is upgrade the industrial structure, Including iIndustrial structure rationality and upgrading of industrial structure two dimensions; FER_{it} is a formal environmental regulation; IER_{it} is a informal environmental regulation; LUE_{it} is a land use efficiency; X_{it} is the control variable; ϵ_{it} is the random interference term.

Considering that there is a certain interaction of environmental regulation on land use efficiency[71], the interaction item of environmental regulation and land use efficiency is introduced in formula (1), and the model setting is extended as follows:

$$ln\ ISU_{it} = \beta\ ln\ ISU_{it} + \alpha_1 ln\ FER_{it} + \alpha_2 ln\ IER_{it} + \alpha_3 ln\ LUE_{it} + \alpha_4 ln\ EFR_{it} \times ln\ LUE_{it} + \alpha_5 ln\ IER_{it} \times ln\ LUE_{it} + \alpha_6 X_{it} + \varepsilon_{it} \tag{2}$$

Due to the spatial effects[72] of ISU, the model (2) did not consider spatial effects. Compared to spatial lag models and spatial error models, the Spatial Durbin Model (SDM) incorporates both the spatial dependence effects of the independent and dependent variables, making it more general. In this paper, we adopt the general form of the SDM model, and the final specification of the spatial panel model is as follows:

$$\begin{aligned} ln\ ISU_{it} = & \beta\sum\nolimits_{i\neq j}\omega_{ij}ln\ ISU_{it} + \alpha_1 ln\ FER_{it} + \alpha_2 ln\ IER_{it} + \alpha_3 ln\ LUE_{it} + \alpha_4 ln\ FER_{it} \times ln\ LUE_{it} + \alpha_5 lnIER_{it} \times ln\ LUE_{it} + \alpha_6 X_{it} \\ & + \gamma_1\sum\nolimits_{i\neq j}\omega_{ij}ln\ FER_{it} + \gamma_2\sum\nolimits_{i\neq j}\omega_{ij}ln\ IER_{it} + \gamma_3\sum\nolimits_{i\neq j}\omega_{ij}ln\ LUE_{it} + \gamma_4\sum\nolimits_{i\neq j}\omega_{ij}lnFER_{it} \times ln\ LUE_{it} + \gamma_5\sum\nolimits_{i\neq j}\omega_{ij}ln\ IER_{it} \times ln\ LUE_{it} + u_i \\ & + v_t + \varepsilon_{it} \end{aligned} \tag{3}$$

In formula(3), ω_{it} represents the spatial distance matrix; α_1、 α_2、 α_3、 α_4、 α_5、 α_6 are respectively the estimated parameters of the formal environmental regulation, informal environmental regulation, LUE, formal environmental regulation and local protection and control variables for ISU; u_i is the region effect, v_t the direct effect, ε_{it} the random interference term. γ_1、 γ_2、 γ_3、 γ_4、 γ_5 are the spatial spillover strengths of both.

3.3. Key explanatory variables

3.3.1. Industrial structure upgrading

The upgrading of industrial structure can be characterized by two dimensions: the rationalization and the advancement of industrial structure [73].

(1) **Rationalized Industrial Structure** : To reflect the adjustment and coordination process of industrial structure, there are various measurement methods such as the deviation degree method [74] and the Theil index method. In this study, Inspired by the methods proposed by many scholars [75,76]; and in comparison with existing approaches to industrial structure rationalization, the reciprocal of the Theil index is adopted as the measure of industrial structure rationalization.

$$RIS = 1 \Big/ \sum\nolimits_{i=1}^{n}\left(\frac{Y_i}{Y}\right)\ln\left(\frac{Y_i}{L_i}\Big/\frac{Y}{L}\right), n = 1, 2, 3 \tag{4}$$

in formula(4) : Y is output value; L is the number of people employed; Yi/Y represents the output structure; Y/L indicates the productivity. The larger the RIS, the higher the degree of rationalization of the industrial structure; The smaller the RIS is, the lower the degree of rationalization of the industrial structure is.

(2) **Advanced Industrial Structure** : The sentence describes the process of industrial structure transitioning from a lower-level form to a higher-level form [77], primarily manifested by the continuous increase in the proportion of the tertiary industry followed by the secondary industry and the primary industry. Following the general approach proposed by Fu Linghui [78], this paper employs the cosine similarity to construct the AIS index (5) (6). $X_0 = (x_{1,0}, x_{2,0}, x_{3,0})$, is the proportion of the added value of the i industry in GDP, then the vectors of x_0 and industry are calculated respectively $X_1 = (1, 0, 0), X_2 = (0, 1, 0), X_3 = (0, 0, 1)$ the Angle θ_1, θ_2, θ_3。

$$\theta_j = \arccos\left\{\frac{\sum_{i=1}^{3}(x_{i,j} \times x_{i,0})}{\left(\sum\limits_{i=1}^{3}(x_{i,j}^2)^{1/2} \times \sum\limits_{i=1}^{3}(x_{i,0}^2)^{1/2}\right)}\right\} \tag{5}$$

$$AIS = \sum_{k=1}^{3}\sum\nolimits_{j=1}^{k}\theta_j \quad j = 1, 2, 3 \tag{6}$$

In the formula, the larger the AIS, the higher the level of industrial structure; the smaller the versa.

3.3.2. Environmental regulation

ER is a policy constraint force aimed at environmental protection [79], reflecting the willingness and intensity of local government in governing the environment. It is manifested in the allocation of funds for environmental protection and regulatory policies on market behavior. Traditional literature primarily examines mandatory environmental regulations formulated by governments, referred to as FER [80,81], with less consideration given to the function of IER. With the enhancement of public environmental

Table 1
ER index system.

Overall indicator level	Sub-indicators	Basic indicators
Environmental regulation	Formal Environmental Regulations	Y1 rate of harmless treatment of household waste (+) Y2 industrial wastewater compliance rate (+) Y3 industrial solid waste utilization rate (+)
	Informal Environmental Regulations	Y4 population density (+) Y5 income level (+)

awareness, various interest groups such as environmental activists and the general public have attached increasing importance to environmental obligations and rights. This study draws on the ideas of Pargal and Wheeler and selects the indicators of income level and population density to comprehensively measure IER. Specifically, areas with higher income levels tend to pursue higher environmental quality and pay more attention to environmental issues.

In densely populated areas, a larger population is affected by environmental pollution, and more people participate in informal environmental regulations. Income level is measured by the average wage of urban residents, while population density is measured by urban population density. Based on this, the study examines both FER and IER, referring to the calculation methods of Martinez Hernandez Juan J and Sanchez Medina Patricia S [82], and Dacey Timothy and Stewart Evan [83]. The Analytic Hierarchy Process is used to obtain the weights of various environmental pollution management results in the sample cities, which are then weighted to derive the level of environmental regulation and construct a comprehensive indicator of environmental regulation (Table 1). Due to the different units of measurement for each indicator and their varying correlations with ER, it is necessary to standardize the indicators to make them comparable for factor analysis.

3.3.3. Land use efficiency (LUE)

LUE is a reflection of the comprehensive productivity of land elements and encompasses multiple indicators that evaluate not only economic benefits but also social and ecological benefits [84]. To establish a comprehensive evaluation system for LUE, it is necessary to consider the effectiveness, systematicness, comparability, and obtainability of the selected indicators. The research of scholars such as Allan Hewitt and Estelle Dominati on LUE evaluation can be referenced [85].

Given the actual situation of the economic development demands and limited land supply[86] in the cities of the CYREB, as well as the need to guide industrial transfer based on differences in land resources, regional resource endowments, ecological environmental capacities, and functional positioning, it is important to promote industrial layout adjustment and optimization, establish interregional cooperation mechanisms for industrial transfer, and leverage the controlling role of land resource management. In accordance with different ecological conditions in different regions, the strategy of delineating priority functional zones for land use [87] should be implemented. This involves integrated planning and allocation of land resources to achieve sustainable development requirements for land use in regional economic development.

In the evaluation of land input [88], indicators such as built-up area of municipal districts, fixed asset investment, and electricity supply are used[89]. Land use input levels are measured based on land structure[90], labor[91], and resource aspects[92], while also examining the level of resource-intensive utilization in cities. In the evaluation of social benefits, indicators such as population density, per capita road area in municipal districts, and infrastructure convenience are used, focusing mainly on residential, transportation, and public space aspects to assess the comfort levels for people in the cities. Economic benefits are assessed using indicators[93] such as per capita fiscal revenue, per capita output value of secondary and tertiary industries, per capita GDP, and residents' income levels[94], primarily considering the level of economic output[95] in cities within the CYREB. Ecological benefits are evaluated using indicators such as greening and waste disposal rates to assess the impact of human activities on the environment. In total, 14 indicators are selected for the evaluation of LUE in cities within the CYREB. A multi-indicator comprehensive evaluation model is employed to determine the weights of each indicator. Comparing various weight determination methods, this study utilizes an improved entropy weight method[96] that constructs weights using entropy values to avoid the issues present in other weight determination methods (Table 2).

3.3.4. Control variable

According to the research conducted by scholars such as Mohsen Mohammadi Khyareh [97], Abdo AlBarakani [98], and Mamkhezri Jamal [99], among them, the external adjustment factors stimulate the optimization of regional industrial structure by affecting the introduction and transfer of provincial industries. After enhancing regional government competition, policy intervention and investment are carried out for regional pillar industries, so as to make regional industrial technology innovation, so as to attract intensive industries to move in, improve regional economic level, feed back regional public construction, promote population

Table 2
Comprehensive evaluation index system of LUE.

Factor	Indicator code	Single factor	Unit	Tendency
land input evaluation C1	X1	built-up area of the urban district	km^2	+
	X2	per capita electricity consumption	10,000 kW-hours/km^2	−
	X3	per capita fixed asset investment	10,000 RMB/km^2	−
social benefit evaluation C2	X4	population density	persons/km^2	+
	X5	per capita road area of the urban district	m^2	+
	X6	convenience of infrastructure	kilometers/10,000 people	+
economic benefit evaluation C3	X7	per capita GDP	10 billion RMB/km^2	+
	X8	per capita total output of secondary industry	10 billion RMB/km^2	+
	X9	per capita total output of tertiary industry	10 billion RMB/km^2	+
	X10	income level	RMB	+
ecological benefit evaluation C4	X11	rate of harmless treatment of household waste	%	+
	X12	rate of compliance of industrial wastewater discharge	%	+
	X13	green coverage rate of the built-up area	%	+
	X14	rate of comprehensive utilization of industrial solid waste	%	+

migration [100], and form a virtuous circle. However, at the same time, if one of the parts develops excessively, it will inhibit regional development. Therefore, these factors have a more comprehensive impact on the regional industrial structure. In this paper, the degree of openness, the level of technological innovation, the level of economic development, the convenience of infrastructure, and government intervention are introduced into the model as control variables. (Table 3). The explanations of these variables are as follows:

①Openness (OPEN): Promoting marketization processes can effectively promote factor mobility and optimize resource allocation. Opening up investment markets and expanding investment areas are conducive to attracting industrial transformation and stimulating regional industrial structure upgrades. However, the transfer of intensive industries may negatively affect LUE due to pollution emissions. In this case, the ratio of total imports and exports to regional GDP is used as a measure[41].
②Technological Innovation Level (INN): It reflects the technological innovation level of a region, which can continuously improve LUE and optimize industrial upgrading [101]. In this case, the ratio of research and development (R&D) expenditure to GDP is used as a measure.
③Economic Development Level (PGDP): When the economic development level of a region is high, production and sales activities of enterprises are more active, and the available space for capital and labor factor allocation increases. There is also an increase in the free flow of factors between different regions and industries. In this case, per capita GDP is used as a measure [102].
④Infrastructure Convenience (INF): Sound infrastructure facilitates reducing the cost of economic operations and provides favorable conditions for industrial development, thereby improving LUE. In this case, the ratio of the length of roads to the total population at the end of the year is used to measure the development of infrastructure[103].
⑤Government Intervention (GOV): Fiscal expenditure is an important means of government macroeconomic regulation. Proper use of regulatory tools can compensate for market failures, improve factor mobility and resource allocation efficiency, and enhance economic externalities. The proportion of local government budgetary expenditure to regional GDP is used as a proxy variable for the degree of government intervention[104].

Please note that the translation may not be word-for-word, but it captures the essence of the original text.

3.4. Panel threshold regression model specification

To further examine and test the non-linear relationship and TE of heterogeneous environmental regulations on LUE, we conducted a regression analysis based on the panel threshold regression model proposed by Hansen (1999) [105]. The specific model is shown as equation (7).

$$ISU_{it} = \alpha_0 + \alpha_1 ER_{it} + \alpha_{21} LUE_{it} \cdot I(q_{it} \leqslant \lambda_1) + \alpha_{22} LUE_{it} \cdot I(\lambda_1 < q_{it} \leqslant \lambda_2) + \alpha_{23} LUE_{it} \cdot I(q_{it} > \lambda_2) + \beta_1 OPRN_{it} + \beta_2 INN_{it} + \beta_3 PGDP_{it} + \beta_4 INF_{it} + \beta_5 GOV_{it} + \varepsilon_{it} \tag{7}$$

In Equation, α_0 is the intercept term, β_1、 β_2 、 β_3、 β_4 、 β_5 are the pending parameters for each control variable, q_{it} is the threshold variable,I (·)is the schematic function, λ_1 and λ_2 are the threshold values for the threshold variables, ε_{it} it is the random perturbation term.

3.5. Data and methodology

The data used throughout this paper are the panel data of 110 cities in the CYREB from 2000 to 2020. The original panel data comes from "China Statistical Yearbook", "China Environmental Statistical Yearbook", "China Science and Technology Statistical Yearbook", "China Industrial Statistical Yearbook", and statistical yearbooks of various provinces and cities. As some years were affected by the epidemic during the period, adjust and timely optimize the existing studies[106]. At the same time, we also refer to many different types of methods and techniques [63], to explain and support the methods in this paper. For some of the missing data, according to the development trend of the data index and the missing type and other attributes, different difference methods are used to supplement. For example, for the positive index of per capita GDP, the linear relationship is fitted according to its development tendency, and the linear interpolation method[107] is used to complete the missing value of some years. For the missing values of the plug-in type in distinct regions, the multiple interpolation method or the establishment of a logistic regression model are mainly used for prediction

Table 3
Variable selection index.

Variable Name	Variable Meaning	Variable Explanation
ISU	Industrial structure upgrading	Industrial structure rationality&Industrial structure advanced
ER (FER)	Formal environmental regulation	Harmless treatment of waste&Utilization of solid waste&Standardized wastewater discharge
ER (IER)	Informal environmental regulation	population density&income level
LUE	Land use efficiency	Land investment&Social benefits&Economic benefits&Ecological benefits
OPEN	Degree of openness	Total import and export volume/GDP
INN	Level of technological innovation	Expenditure on research and development/GDP
PGDP	Level of economic development	Per capita GDP
INF	Degree of infrastructure convenience	Length of operational highways/Total population at the end of year
GOV	Government intervention	Local government budget expenditure/GDP

and filling[50]. For the continuous missing data, the mean value is utilized to supplement. In view of the two aspects of environmental regulation, the optimized entropy weight method is used for comprehensive calculation to obtain the overall level of environmental regulation. Finally, in order to eliminate the influence of different dimensions of each index, the range method is used to standardize the original data, and then the logarithm of each index is taken to overcome the impact of heteroscedasticity and multicollinearity.

The main research question of this paper is the impact of ER and LUE on the ISU. At the same time, it examines the non-linear relationship and TE of heterogeneous environmental regulation on the ISU through the effect of LUE. The principal method used in the empirical analysis is the spatial econometric analysis method. The spatial econometric model is established and the hypothesis is proposed that heterogeneous environmental regulation and LUE have no effect on the ISU. After putting forward the hypothesis, Stata MP 17 (64-bit) software is utilized to import the processed panel data for OLS regression analysis. At the same time, LM test, Robust LM test and Hausman test are performed. Depending on the test results and significance, the accuracy of the hypothesis is judged, and the spatial econometric model suitable for CYREB is determined. Therefore, considering the particularity and relevance between China 's administrative regions[108], the weight matrix set in this paper is a latitudinal distance matrix, and the relationship between regions is established by linear Euclidean distance. Then, according to the model, the spatial effect of the RIS and AIS of the CYREB is decomposed and analyzed, and the threshold and effect of heterogeneous environmental regulation on the CYREB are determined under the threshold model. From the spatial level to study the overall adjacency relationship and the overall structural development.

The pre-evaluation and analysis of the results mainly focus on the spatial effect analysis of the RIS and AIS, decompose the spatial effect, and determine the influence trend and size and significance between regions with the positive and negative values of the spatial effect and its P value[109]. According to the results, the adjacent relationship between regions is predicted and analyzed, and the threshold effect is based on the determined threshold value and the positive and negative values of the effect of heterogeneous

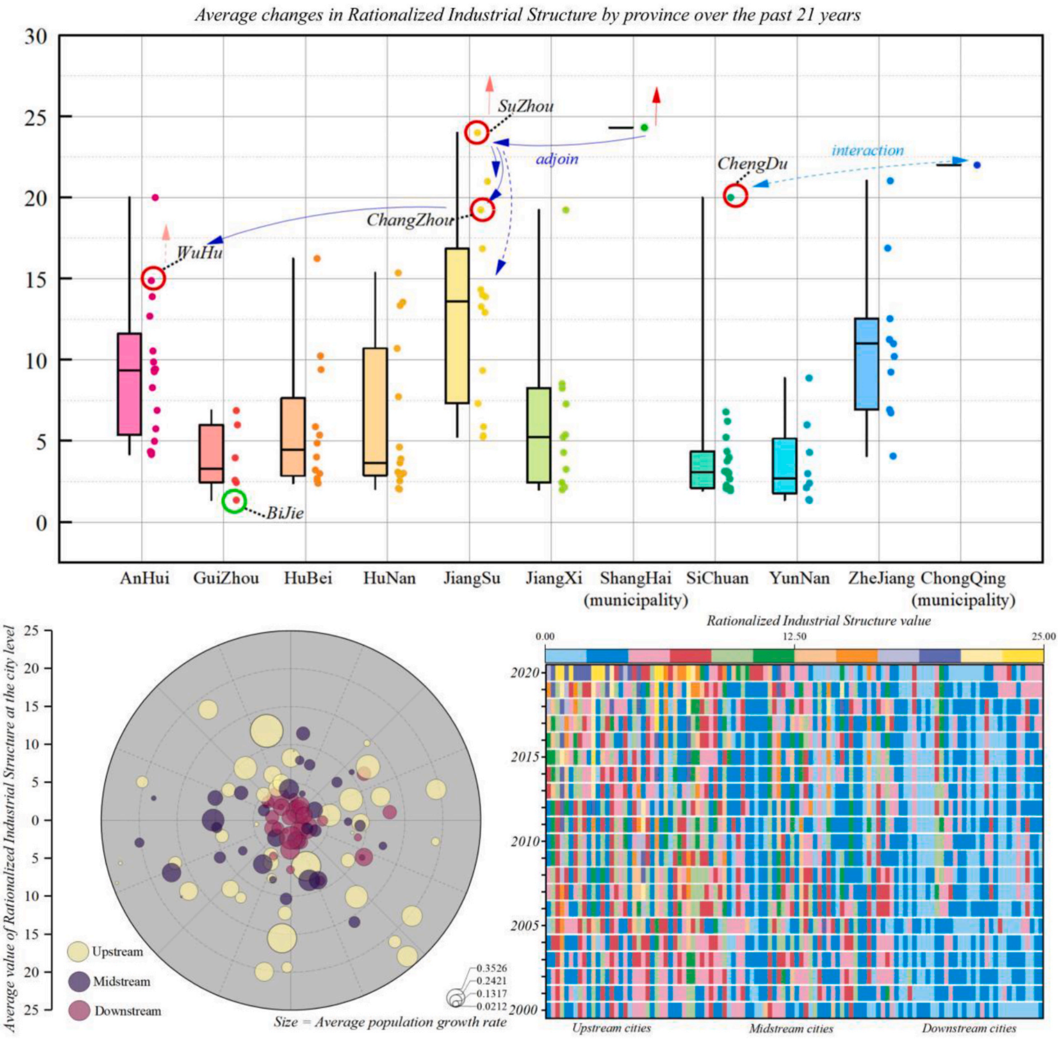

Fig. 3. Level of RIS in the upper, middle and lower reaches of the CYREB.

environmental regulation on the industrial structure to determine that the heterogeneous environmental regulation promotes or inhibits the development of the ISU, so as to obtain the nonlinear relationship of its role.

4. Result analysis

4.1. Industrial structure

4.1.1. Rationalized industrial structure

Based on the calculation of the average RIS, the level of industrial rationalization can be assessed. From Fig. 3, it can be observed that the overall level of industrial structure rationalization shows an upward trend, with the downstream region having the highest level, followed by the midstream region, and the upstream region having the lowest level.

The RIS level in the downstream region has shown a clear upward trend over the years. In the midstream region, there are fluctuations in some years, which may be attributed to regional policy adjustments. In the upstream region, due to its relatively backward industrial facilities, unchanged transportation infrastructure, sparse population density, and other factors, has lower average RIS levels for each city. This indicates that the industrial structure allocation in the upstream region is not sufficiently rational, and the utilization of industrial resources is not optimal.

When comparing different river basins with the overall CYREB, it can be seen that the RIS index in the downstream region has consistently been higher than the overall level. By expanding in a diffusion manner from the downstream cities towards the western region, it could promote rational resource allocation in the midstream and upstream regions, improve the level of industrial structure rationalization, and facilitate the overall ISU across the entire river basin.

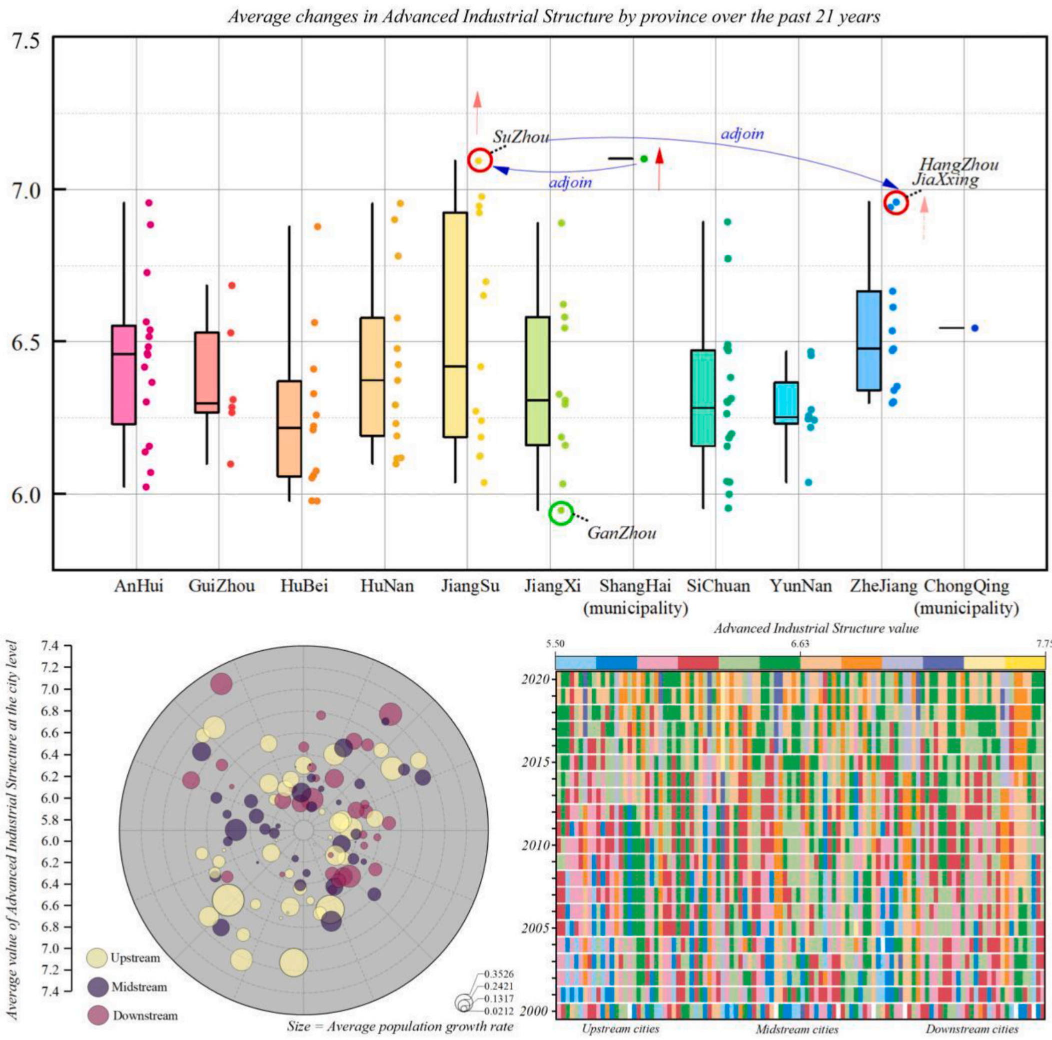

Fig. 4. Level of in AIS in the upper, middle and lower reaches of the CYREB.

4.1.2. Advanced industrial structure

By calculating the AIS index, the distribution of AIS can be observed. From Fig. 4, it can be seen that the overall level of industrial structure advancement shows an upward trend, indicating a transformation from a lower-level "primary-secondary-tertiary" form to a higher-level "tertiary-secondary-primary" form in the CYREB. Specifically, the AIS level shows a decreasing pattern from downstream to upstream. Among them, the changes in the cities in the downstream region are the most significant. From 6.1187 in 2000, it increased to 7.4923 in 2020, an increase of 1.3736. This is largely due to the strong overall economic capabilities of downstream cities, such as Shanghai and Hangzhou, which are primarily dominated by the tertiary industry, followed by the secondary industry. In particular, Shanghai's tertiary industry accounted for 70.93%, 72.88%, and 73.15% in 2018, 2019, and 2020 respectively. Recently, through industrial transfers, a plethora of productive enterprises have been relocated from the downstream region to the midstream and upstream regions, such as Chongqing and Wuhan. Wuhan, for example, increased from 6.0125 in 2000 to 6.7742 in 2020. However, some cities in the downstream region exhibit a fluctuating pattern of "rise-fall-rise," such as Chongqing, which increased from 5.8919 in 2000 to 6.3978 in 2005, then decreased to 6.0114 in 2015, and finally increased again to 6.7712 in 2020.

4.2. Environmental regulation

4.2.1. Temporal changes in environmental regulation

From Fig. 5, it can be seen that overall, the comprehensive intensity of environmental regulation exhibits a fluctuating pattern. In 2012, regardless of the overall trend or the se-gmentation into upstream, midstream, and downstream, there was a noticeable decrease and increase in the intensity. The overall intensity showed a similar fluctuation pattern to the segmented intensity.

In terms of segmentation into upstream, midstream, and downstream, especially in the downstream cities of the Yangtze River, for instance Shanghai, Suzhou, Nanjing, and Hangzhou, which are economically developed, the government has stronger efforts in waste reduction and ecological conservation, resulting in greater environmental constraints. The midstream cities of the Yangtze River region have a level of environmental regulation that is in line with the upstream cities, and the environmental regulations are adjusted accordingly. The upstream cities, from the perspective of the overall mean intensity of ER, show weaker intensity compared to the other two regions, which may be due to the influence of the industrial structure in the upstream region.

Overall, the continuous strengthening of ER has increased the utilization and treatment rate of "three wastes" (waste gas, waste

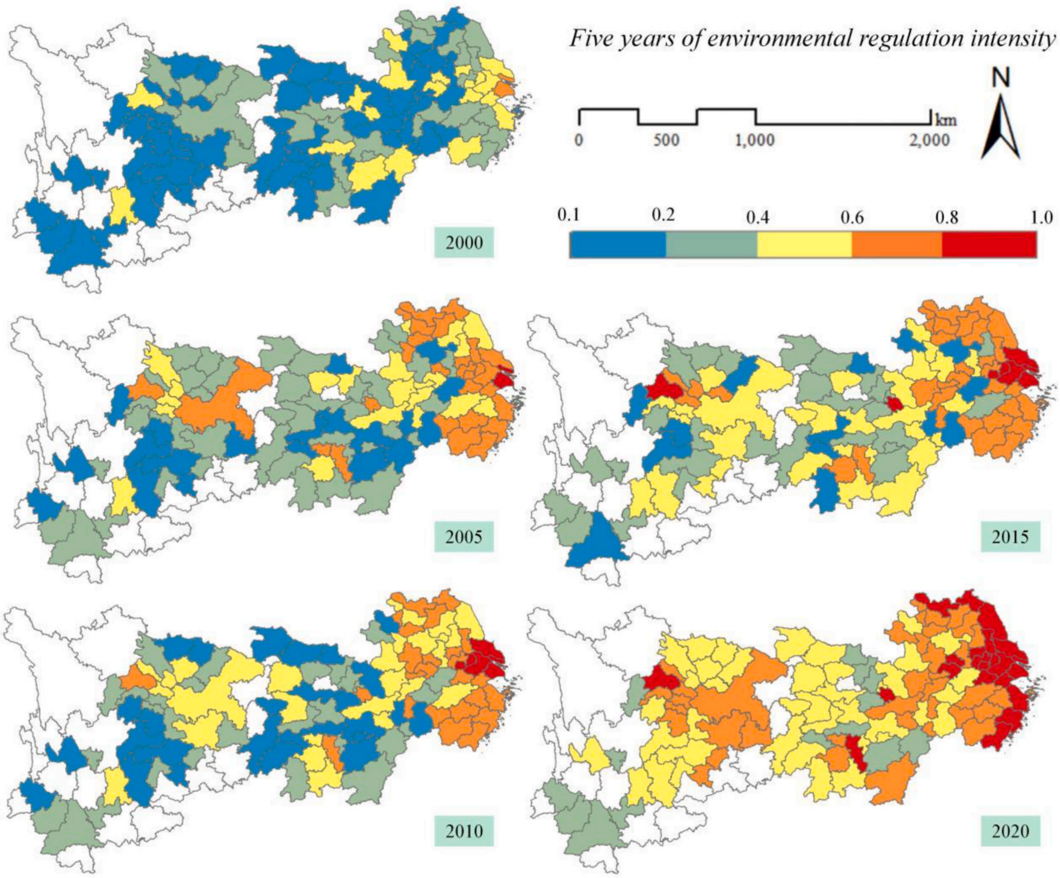

Fig. 5. Spatial evolution of urban ER level in the Yangtze River Economic Belt.

water, and solid waste), thereby enhancing the pollution prevention and control capabilities of cities along the CYREB. This has indirectly contributed to population growth to some extent and promoted the optimization and upgrading of industrial structure.

4.2.2. Spatial changes in environmental regulation

From a spatial perspective (Fig. 5), the environmental regulations exhibit spatial variations, gradually decreasing from east to west. Specifically, the eastern downstream region (Shanghai, Hangzhou, Suzhou) has the highest level of ER, reflecting the developed economy and strong environmental constraints in these cities. They have strong capabilities in pollution reduction and treatment. The next highest level is found in the central cities of the western upstream region, including Kunming, Chengdu, and Chongqing. The middle and midstream regions have lower levels of ER, with slower economic development in cities such as Huaihua, Huanggang, and Yichang.

Overall, the environmental regulation level in each region shows a gradual upward trend. For example, in the upstream region, it increased from 0.2776 to 0.4996. Looking at individual cities, the level of environmental regulations varies significantly. For example, in 2010, the highest level was found in Shanghai (0.9644), while the lowest was in Huaihua (0.1845), with a range of 0.7799. By 2020, the highest level was still in Shanghai (0.9915), while the lowest was in Nantong (0.1101), with a range of 0.8814.

These findings reflect the uneven development of ER among cities along the CYREB in China, as well as significant differences in the attitudes and capabilities of pollution-intensive enterprises. Moreover, the disparities are increasing.

4.3. Land use efficiency

From the LUE index of 110 prefecture-level cities from 2000 to 2020, the following four years can be seen that the overall housing price of CYREB is on the rise (Fig. 6). In this regard, the downstream region had higher efficiency, followed by the middle region, and the upstream region had the lowest efficiency. Cities in the downstream region, such as Shanghai and Suzhou, achieved relatively high LUE levels of 0.9251 and 0.8864, respectively, with a noticeable upward trend over the years. The average LUE levels in cities of the

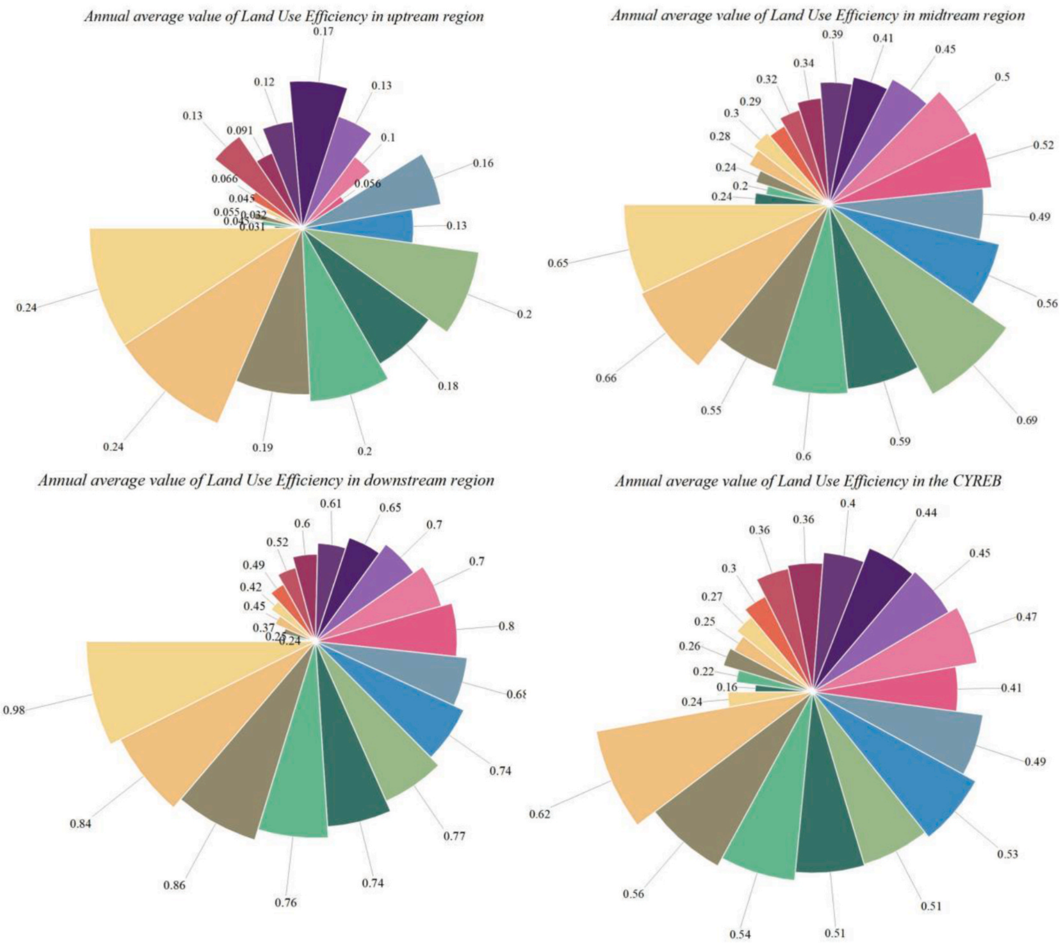

Fig. 6. LUE in the upper, middle and lower reaches of the CYREB.

middle and upstream regions were relatively lower but showed a continuous increase, indicating an overall upward trend in LUE in all regions.

This trend aligns with China's "planning-supply-regulation-optimization" approach to green transformation, which involves spatial control, market allocation, incentive constraints, and land resource management strategies. Through scientific industrial spatial planning, stringent ecological environment access control, and guiding land resources towards new industries, new formats, and high-quality, efficient enterprises, the policy aims to promote the transformation and upgrading of low-efficiency land by innovating diverse utilization methods and promoting interregional industrial transfer cooperation. It thus contributes to the green transformation of land resource utilization and development in the CYREB.

Looking at the distribution of data for each year, the data in the CYREB tends to be concentrated within the range of 0.2–0.6. In most years, the data in the downstream region is above the average, indicating a relatively higher distribution of LUE values, mainly concentrated in the range of 0.6–0.9. The data distribution in the middle region is relatively symmetrical, while in the upstream region, the data for each year is concentrated at lower levels, primarily within the range of 0–0.2, indicating relatively lower LUE values overall.

4.4. The impact of heterogeneous environmental regulation and land use efficiency on industrial structure upgrading

4.4.1. Spatial correlation analysis

Before applying spatial econometric models for analysis, it is necessary to verify the spatial correlation of indicators related to ISU to support the need for using spatial econometric models. In this study, Stata17 (64-bit) software was used to calculate the Moran's I index for both industrial structure rationalization and advanced upgrading, as shown in Table 4.

From Tables 4 and it can be observed that the Moran's I index for both industrial structure rationalization and advanced upgrading is greater than 0. Additionally, for most years, both rationalization and upgrading of the industrial structure show significant positive spatial correlation at a significant level, passing the significance test. This reveals the presence of significant spatial spillover effects in the rationalization and upgrading of the industrial structure, which have a positive impact on surrounding areas. Therefore, when constructing the spatial Durbin model for green total factor productivity, it is essential to consider its spatial effects.

4.4.2. Model selection for overall estimation

Before conducting analysis with spatial econometric models, it is necessary to determine whether spatial correlation is driven by the error term or lagged variables. This can be achieved through LM and Robust LM tests. Additionally, Wald tests and likelihood ratio tests can be used to determine if the spatial Durbin model can be simplified to spatial error or spatial lag.

From Table 5, it can be observed that the estimation results indicate that both LM-spatial lag and LM-spatial error pass the significance tests at the 1% and 5% levels, respectively. Furthermore, the robustness tests also pass the significance test at the 1% level. However, the significance of the spatial lag model is stronger, indicating that the spatial lag model is superior to the spatial error model. This also suggests that environmental regulations and LUE have a significant spatial correlation with the rationalization of industrial structure.

Table 4
Industrial structure rationalization and advanced Moran's I.

year	Rationalized Industrial Structure		year	Advanced Industrial Structure	
	Moran's I	*P*-value		Moran's I	*P*-value
2000	0.049***	0.000	2000	0.002	0.243
2001	0.051***	0.000	2001	0.013***	0.006
2002	0.070***	0.000	2002	0.006*	0.068
2003	0.053***	0.000	2003	0.018***	0.007
2004	0.076***	0.000	2004	0.012**	0.021
2005	0.082***	0.000	2005	0.005	0.216
2006	0.107***	0.000	2006	0.008*	0.073
2007	0.143***	0.000	2007	0.001*	0.086
2008	0.142***	0.000	2008	0.001***	0.004
2009	0.117***	0.000	2009	0.002*	0.065
2010	0.110***	0.000	2010	0.004**	0.022
2011	0.117***	0.000	2011	0.036***	0.000
2012	0.121***	0.000	2012	0.029***	0.000
2013	0.133***	0.000	2013	0.004***	0.008
2014	0.137***	0.000	2014	0.009*	0.098
2015	0.142***	0.000	2015	0.006*	0.071
2016	0.138***	0.000	2016	0.016***	0.001
2017	0.126***	0.000	2017	0.001*	0.064
2018	0.115***	0.000	2018	0.008	0.459
2019	0.127***	0.000	2019	0.010***	0.002
2020	0.165***	0.000	2020	0.020***	0.000

annotation: ***、**and* indicate significance at the 1%, 5%, and 10% levels, respectively, and the same applies for the subsequent results.

Table 5
Industrial structure rationalization space measurement inspection results.

Test Method	Statistic	Probability	Test Method	Statistic	Probability
LM-spatial lag	22.961	0.004	Wald-spatial lag	33.854	0.000
Robust LM-spatial lag	30.889	0.000	LR-spatial lag	88.215	0.001
LM-spatial error	3.737	0.053	Wald-spatial error	43.541	0.002
Robust LM-spatial error	11.665	0.001	LR-spatial error	56.204	0.001

In addition, by constructing the SDM and conducting Wald tests and likelihood ratio tests, it is possible to determine whether the SDM can be simplified to SAR and SEM. The results show that Wald-spatial lag, Wald-spatial error, LR-spatial lag, and LR-spatial error all pass the significance test at the 1% level and combined with the Hausman test result 145.29 ($p = 0.000$), the null hypothesis is rejected and the SDM cannot be reduced to SAR or SEM, so the spatially fixed Dubin model is selected.

4.4.3. Spatial effects analysis

According to Table 6, the direct effect of the explanatory variable FER is 0.1734, but it is not significant. However, the indirect effect is significant at −0.6540. This indicates that the increase in pollution control costs brought about by FER can encourage the rational allocation of industrial structure, with production factors flowing towards industries with lower pollution. However, compared to the high profits brought by high-pollution industries, this effect is not significant. Additionally, the increase in local ER leads to an increase in production costs, causing polluting industries to migrate to neighboring provinces with more lenient environmental policies. This significantly reduces the level of industrial structure rationalization in those provinces, indicating the existence of a "pollution haven" in China.

The direct effect of IER on industrial structure rationalization is significantly −0.1825, while the indirect effect is not significant. Due to the overall low education level of the Chinese workforce, but with a large population and sufficient cheap labor, industries related to the primary sector tend to have lower incomes, while the threshold for entering industries related to the tertiary sector is higher. As a result, the population tends to flow into the secondary sector, which offers higher income levels and has a greater demand for labor.

Since the cost of innovation for industrial enterprises is higher than external costs, these enterprises tend to focus on tackling environmental issues through end-of-pipe treatment methods rather than investing in technological research and development. The additional costs further compress the profit margins of the enterprises and hinder technological innovation, thereby inhibiting the ISU.

The utilization of land resources by local governments has a significant impact on the development of industrial structure, resulting in misallocation of resources and evident constraints on the rationalization of the local industrial structure. At the same time, the efficiency of land use also hinders the rationalization of industrial structure in neighboring provinces to some extent. To study the intervention of LUE in environmental regulations, the interaction term of LUE with FER and IER was included. The results show that the direct effect of the interaction term between formal environmental regulations and LUE is 0.0650, but it is not significant. However, the indirect effect is significant at −0.8009. This indicates that the interaction term between formal environmental regulations and LUE has a limited promoting effect on the rationalization of local industrial structure, but significantly inhibits the rationalization of industrial structure in neighboring regions. On one hand, with the reinforcement of local ER and the prioritization of economic development over the protection of low-end industries by local governments, these industries tend to migrate to neighboring provinces. On the other hand, the bolstered environmental regulations and enhanced environmental quality attract a greater influx of high-end talents and high-tech industries to the region, indirectly impeding the optimization of industrial structure in neighboring provinces.

The direct effect of the interaction term between IER and LUE is significant at −0.1031, but the indirect effect did not pass the test. This indicates that IER and LUE have an impact on the rationalization of industrial structure in neighboring provinces, while also having a suppressive effect on the rationalization of local industrial structure. This is mainly due to the high population density and strengthened IER in the region, where local governments have the dual responsibility of ensuring employment rate and environmental protection. To promote employment, they are compelled to attract manufacturing industries, which is not conducive to the

Table 6
Rationalized Industrial Structure space fixed effect decomposition.

Variable	Direct Effect		Indirect Effect		Total Effect	
	Coefficient	t-value	Coefficient	t-value	Coefficient	t-value
lnFER	0.1734	0.1582	−0.6540	0.9555	−0.4807	0.9126
lnIER	−0.1825*	0.1049	−1.8974	1.0179	−2.0799**	1.0136
lnLUE	−0.1095	0.2059	−0.5152	1.4217	−0.6246	1.4029
lnOPEN	−0.1927**	0.0089	−0.1951*	0.0920	−0.2143**	0.9216
lnINN	−0.4901**	0.0194	−0.0686	0.2359	−0.1176	0.2429
lnPGDP	−0.020	0.2290	−0.7213**	0.2965	−0.7233**	0.3019
lnINF	0.0108	0.0485	−0.8157	0.4315	−0.0707	0.4244
lnGOV	0.0025	0.0309	0.1572	0.4049	0.0182	0.4166
lnFER*lnLUE	0.0650	0.0695	−0.8009*	0.4706	−0.7359	0.4535
lnIER*lnLUE	−0.1031**	0.0415	−0.1678	0.4021	−0.2709	0.4013

Table 7
Advanced Industrial Structure space fixed effect decomposition.

Variable	Direct Effect		Indirect Effect		Total Effect	
	Coefficient	t-value	Coefficient	t-value	Coefficient	t-value
lnFER	0.2854	0.1582	−0.5401***	−0.8792	−0.1814*	−1.9825
lnIER	0.0214	0.2541	−1.3574	−1.0192	−2.0921	−0.0613
lnLUE	0.9105**	0.4571	−0.2589***	−0.7214	−0.4627	−1.9014
lnOPEN	0.1247	0.8921	−0.5121	−0.2021	0.1431	0.2167
lnINN	0.0124	0.0458	0.0166**	0.3527	0.1257**	0.2291
lnPGDP	0.2017***	1.2277	−0.2135***	−0.2977	0.2331***	0.2471
lnINF	−0.0087*	−0.4571	0.0547***	0.4151	0.2588***	0.4415
lnGOV	0.0051	0.0097	0.5722	0.4937	0.0122	0.6615
lnFER*lnLUE	0.0501	0.6951	−0.0927***	−0.7061	−0.3519**	−0.5110
lnIER*lnLUE	0.0031	0.1524	−0.7125	−0.0215	−0.7091	−0.0134

Regarding IER, the direct effects of IER and the interaction term between IER and LUE are 0.0214 and 0.0031 respectively, and the indirect effects are negative but not significant. This indicates that higher levels of IER and larger values of the interaction term may lead to higher levels of industrial structure sophistication, but the effect is not very pronounced. Moreover, it may also restrain the improvement of industrial structure sophistication in surrounding areas.

improvement of industrial structure rationalization. Additionally, although the economic level of the CYREB has significantly improved in recent years, the upstream regions still have a relatively weak economic foundation. Local governments need to protect industrial enterprises to drive economic development, directly affecting the rationalization of the local industrial structure.

According to Table 7, the direct effects of formal environmental regulations and the interaction term between FER and LUE are 0.2854 and 0.0501 respectively, but neither of them is significant. However, the indirect effects are significant and they are −0.5401 and −0.0927 respectively. For the CYREB, the implementation of FER has led to an increase in the cost of pollution control for enterprises. This necessitates local companies to acquire new pollution control equipment or pioneer environmental technologies, escalating technological and capital thresholds for new entrants. Consequently, firms are compelled to transition towards the less-polluting tertiary sector, thereby refining the sophistication of their industrial structures. Meanwhile, stringent environmental regulations drive highly polluting industries to areas with laxer policies, causing a notable downturn in industrial sophistication in neighboring regions, while the LUE mechanism curbs industry relocation to adjacent areas.

The direct effects of LUE and economic development level are significant at 0.9105 and 0.2017 respectively, while the indirect effects are significant at −0.2589 and −0.2135 respectively. Local governments have a dual responsibility to protect local enterprise development and the environment. They can provide fiscal subsidies to environmental protection enterprises, encourage environmental protection, and promote the transformation of industries from highly polluting secondary industries to less-polluting tertiary industries, thus facilitating the advancement of industrial structure sophistication.

4.4.4. Robustness test

For the sake of investigate the robustness of the estimated results and make full use of the panel data, this paper adopts the adjustment model method to test, specifically: AIS and RIS are not only by the opening to the outside world, government intervention, but also by the labor cost and product consumption trend factors [110,111], therefore, this paper adds the control variables in the model, to test the stability of the model. High labor costs (LC) will promote enterprises to adopt more technology upgrades and automation equipment to replace artificial labor, so as to achieve the purpose of technological innovation [112], which will improve production efficiency, reduce production costs, and promote the industrial structure towards a more advanced direction. At the same time, the change of product consumption trend (PCT) will affect the layout and structure of the industry. When a certain industry or product is favored by consumers, the enterprises in the relevant industrial chain will tend to increase their investment and development, and form a certain industrial cluster. Such adjustment can promote the coordinated development of related industries and improve the overall level of upgrading. Consumer trends also have an impact on the direction and speed of technological innovation. When consumer demand turns to novel and innovative products, enterprises will tend to make technological innovation to meet the market demand, and promote the upgrading of industrial structure[113]. According to the analysis results (Table 8 (1)), the core explanatory variables FER, IER and LUE are close to the benchmark model, so the above model is robust.

Both ER and LUE have certain spatial and temporal dynamics [50]. For the sake of test the robustness of the estimated results, the ER measures were replaced with ER_{+1} according to the measures of environmental regulation in the study by Guo F and Gao S [114] et al. Replace the LUE measure, According to the measurement index of LUE [115] in the people on the impact of new urbanization on LUE, Replace it with LUE_{+1}. From the results (Table 8 (2) (3)), Regardless of which indicator is used to measure LUE and ER, The core explanatory variables FER, IER as well as LUE remained significant, It shows that the ER index and LUE index are more suitable, It can well reflect the environmental policy changes and the fluctuations of LUE in the CYREB.

4.4.5. Threshold effect analysis

Due to the heterogeneity of ER, the ISU is further influenced by its impact on LUE. LUE is characterized by both “offsetting effects” and “compensatory effects"[116], suggesting the presence of a “threshold effect” in the role of ER [117]. Therefore, it is imperative to explore and elucidate the characteristics of these impact effects to provide insights for targeted FER and IER policies.

Table 8
Rationalized Industrial Structure and advanced robustness test.

variable	Rationalized Industrial Structure (RIS)			Advanced Industrial Structure (AIS)		
	New control variable	(ER_{+1})	(LUE_{+1})	New control variable	(ER_{+1})	(LUE_{+1})
	(1)	(2)	(3)	(1)	(2)	(3)
lnFER	−0.0201** (−1.0329)	−0.3965*** (−1.1104)	−0.2289*** (−0.8864)	−0.1358*** (−3.8452)	−1.0025*** (−1.0251)	−0.1997*** (−0.2841)
lnIER	−0.0127*** (−0.2945)	−1.0108*** (−0.3361)	−0.1254* (−1.2879)	−1.0721* (−0.3217)	−2.0399** (−0.2561)	−0.2812* (−0.8873)
lnLUE	−0.2254* (−0.1212)	−0.2365** (−0.3010)	−1.2650.* (−0.2001)	−2.3600* (−1.2567)	−0.3124* (−0.7410)	−1.4215* (−0.9123)
lnLS	0.2879*** (0.8895)			1.3601*** (0.4401)		
lnPCT	0.3601*** (1.2549)			0.3324** (0.6597)		
lnFER*lnLUE	−0.2304 (−0.3361)	−0.0031 (−1.2870)	−0.1233* (−0.3999)	−0.1145* (−0.9165)	−0.2106* (−0.1990)	−0.3349 (−0.2514)
lnIER*lnLUE	−0.0254 (−0.1039)	−0.1254 (−0.2510)	−0.0008 (−0.2100)	−0.0201* (−0.3331)	−0.0206 (−1.3687)	−0.3001* (−0.5200)
p	0.3200*** (10.3564)	0.1256*** (8.7623)	0.5297*** (4.3654)	0.0325*** (2.88869)	0.2501*** (2.0125)	0.3480*** (1.0300)
R2	0.9235	0.9124	0.9601	0.9520	0.9836	0.9403

annotation: * * *, * * and * are significant at 1%, 5% and 10%, respectively; t statistic in brackets.

Here, two indicators, RIS and AIS are used to measure the level of ISU as the dependent variable. Two alternative threshold variables are set: one is the FER as the explanatory variable, and the other is the IER as another independent variable. Threshold effect tests are conducted on these two alternative threshold variables, and the test results are shown in Table 9.

According to Fig. 7, the dual-threshold model rejects the null hypothesis at the significance level of 1% when AIS and RIS are used as explanatory variables and FER is used as the threshold variable. Therefore, the dual-threshold model is chosen to analyze the impact of ER on the ISU of manufacturing through the influence on LUE. The results of panel threshold regression are shown in Table 10, which only presents the regression results of the core explanatory variables that require specific analysis.

When the intensity of ER is below the threshold value of 0.0315 (Fig. 7), the increase in pollution costs for local governments and enterprises is relatively small. Local governments can compensate for these costs by reducing costs in other areas and improving production efficiency. Therefore, it is not enough to stimulate local governments to improve LUE. On the contrary, the increase in pollution costs may inhibit the rational use of land resources. In this situation, local governments will continue to maintain their current production patterns and land use, thereby suppressing the ISU of local.

When ER intensity falls between 0.0315 and 0.0886, it still constrains LUE and ISU but to a lesser degree. Beyond 0.0886, ER positively influences LUE, indicating mutual promotion. Despite increased pollution costs, local governments and enterprises can offset them by enhancing LUE, thus improving production efficiency and profitability. This compensatory effect prompts the rational application of land resources integration and improved LUE to promote local industrial structure upgrades.

The above threshold regression results indicate that the heterogeneous ER do not have a simple linear relationship with the impact on LUE and ISU. Instead, there is a dual threshold effect, where the intensity of ER has a “strong restraint-weak restraint-mutual promotion” effect on LUE. As a result, it has a inhibitory effect on ISU at first and then a promoting effect.

5. Discussion

The central research inquiry of this paper revolves around assessing the impact of heterogeneous ER on the ISU under the influence of LUE. Employing the spatial Dubin model facilitates the exploration of spatial factors influencing the AIS and RIS. Furthermore, the utilization of the threshold model corroborates that the impact of heterogeneous ER on the ISU, under the modulation of LUE, is not a simple linear relationship. Building upon the aforementioned analysis, this paper delves into the following research outcomes, conducts comparisons with existing studies [118–120], critiques the limitations, proposes improvements, and undertakes a deeper exploration of the grasp and prospects for future directions.

The impact of environmental regulation on industrial structure is heterogeneous. The empirical results of this paper show that

Table 9
Results of the TE test.

Dependent Variable	Threshold Variable	Single Threshold		Double Threshold		Triple Threshold	
		F-statistic	*P*-value	F-statistic	*P*-value	F-statistic	*P*-value
AIS	IER	55.55***	0.0100	24.64	0.2267	13.33	0.7467
	FER	150.00**	0.0367	74.82***	0.0000	24.33	0.7867
RIS	IER	7.02	0.4600	2.07	0.8600	4.32	0.5233
	FER	133.71***	0.0000	69.45***	0.0100	22.76	0.7067

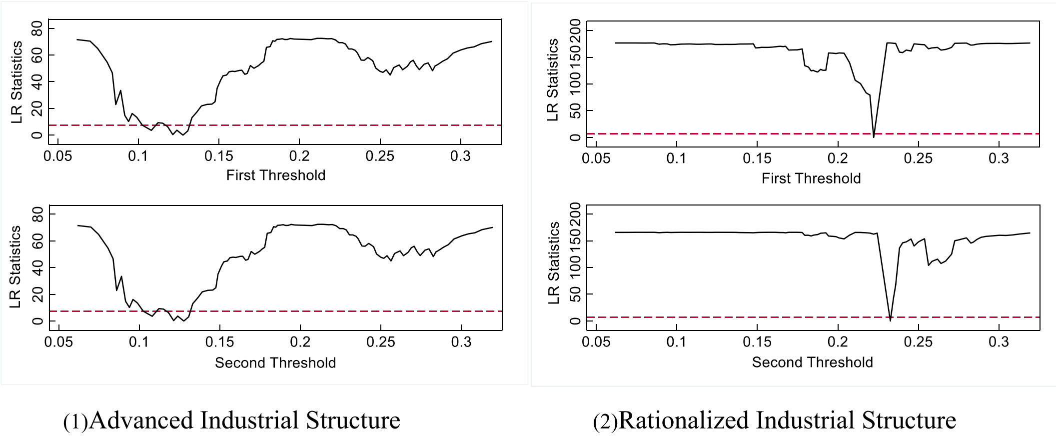

Fig. 7. The LR plot of the threshold test.

Table 10
Results of the threshold-effect regression.

independent variable	Threshold Variable FER
LUE (FER≤0.0315)	−0.3152***
	(0.0058)
LUE (0.0315 < FER≤0.0886)	−0.0238***
	(0.0275)
LUE (FER > 0.0886)	0.0004*
	(0.0417)
N	360
R^2	0.3847
F-statistic	102.3600

formal environmental regulation significantly encourages the development of regional industrial structure rationalization and upgrading, and has a significant positive spatial effect on neighboring areas. With the improvement of informal environmental regulation, the level of rationalization of local industrial structure has decreased significantly, and the level of rationalization and upgrading of industrial structure in neighboring cities has also decreased. This also leads to the transformation of the industrial structure of the CYREB from the lower form of "primary industry, secondary industry and tertiary industry" to the higher form of "tertiary industry, secondary industry and primary industry", but there are obvious differences among regions, showing a decreasing pattern of lower, middle and upper reaches. This result is similar to some existing research conclusions [121], and also reflects the role of environmental regulation in promoting industrial structure [122]. The difference mainly lies in that some studies do not take into account the impact of informal environmental regulation [123], or there are certain differences in the selection of environmental regulation indicators and research areas[124]. Based on the environment of green development[125], this paper focuses more on the quantitative description of environmental indicators[126]. The main significance of this conclusion is to promote the green transformation of key industries[11], strictly implement the dual control of energy consumption, resolutely curb the blind development of "two high" projects, promote the solution of the bottleneck problem of realizing the value of ecological products, comprehensively promote the optimization and upgrading of industrial structure, promote the upgrading of industrial foundation and the rationalization of industrial distribution, and shape the new advantages of innovation-driven development under the background of China 's environmental policy adjustment and optimization of energy structure [90].

ER introduces the "pollution heaven phenomenon" to the CYREB. Historically, the non-independence and external characteristics of ER [127] have resulted in varying levels of ER among regions at different stages of development, driven by distinct developmental demands and environmental sensitivities [128]. This has raised concerns regarding the "Pollution Paradise" hypothesis [129]. Through thorough research and analysis, the "pollution paradise" phenomenon becomes evident in the CYREB. Regional changes in industrial structure reveal the notable spatial effects of ER on industrial composition. This prompts the shift of regional industries from areas with stringent ER to neighboring regions with more lenient regulations, consequently resulting in a "pollution paradise" scenario [130]. The reform of the performance appraisal system at the central government level diminishes the inclination of local governments to host polluting enterprises [131]. This action blocks cross-regional channels for the transfer of polluting enterprises, instigating adjustments in regional environmental regulations and comprehensive land utilization. These adjustments compel polluting enterprises to confront the costs of compliance. Indigenous innovation plays a pivotal role in reducing internal friction related to pollution control [132], thereby unleashing the "Porter effect" of ER. In current research, some studies leverage the spatial Dubin model for analysis [133,134], yielding insights into the spatial effects of ER on the development of neighboring regions. The emphasis lies in the complex interaction between diverse ER and LUE, which molds regional industrial structure. This focus stems from the belief that LUE drives local economic development, establishing a close relationship and mechanism with ISU. The significance of LUE extends to national development. Building upon existing studies, this paper introduces an additional research hypothesis: as global industrialization advances, the emergence of the "pollution haven" phenomenon may be intricately linked to industrial structure dynamics. The sensitivity of this phenomenon is expected to intensify with the proximity of these factors [135,136].

There is a complex endogenous mechanism among environmental regulation, land use and industrial structure upgrading. Heterogeneous environmental regulation reverses the upgrading of industrial structure through the impact on land use efficiency, and land use efficiency has both "offset effect" and "compensation effect". Similar to some research results, the role of heterogeneous environmental regulation has a "threshold effect" [105]. The analysis of this paper shows that when the intensity of environmental regulation is less than the threshold value of 0.0315, due to the relatively small increase in the cost of sewage discharge brought by environmental regulation to local governments and enterprises, local governments can make up for the cost of sewage discharge by compressing the cost of other links and improving production efficiency. Therefore, it is not enough to force local governments to improve the efficiency of land use. On the contrary, due to the increase of a certain amount of sewage discharge, it will inhibit the rational use of land resources. At this time, local governments will continue to maintain the original production mode and land use status, thus inhibiting the upgrading of local industrial structure.

When the intensity of environmental regulation is greater than the threshold value of 0.0315 and less than 0.0886, environmental regulation still inhibits land use efficiency and industrial structure upgrading, but the degree of inhibition has declined. When the intensity of environmental regulation is greater than the threshold value of 0.0886, environmental regulation has a positive effect on land use efficiency, indicating that there is an interaction between the two. It is not difficult to understand that for a transitional developing country like China, in the early stage of economic development, the market-oriented economic system has not been perfected[137], and the relevant policies of environmental regulation are not perfect enough. Planned government intervention in resource allocation is deemed apt for current economic and industrial structure development, facilitating phased rapid industrial growth. However, weak regional environmental regulation leads to inefficient land use, impeding industrial structure upgrading.

When the market economic system is gradually improved, the market begins to think about whether it can be further optimized in the rationalization and upgrading of industrial structure and environmental carrying capacity [138]. The green industry development model under environmental regulation has become the main driving force for green economic growth and industrial structure optimization. At this stage, environmental regulation has played a significant role in promoting the rationalization and upgrading of industrial structure. After crossing the second threshold, the inhibitory effect of environmental regulation on the optimization and adjustment of industrial structure began to weaken, and gradually turned to promote the interaction with land use efficiency. Through the above analysis, we can get the mechanism of action between the three (Fig. 8). Compared with the current research of Chang et al. the difference is that the study simply takes into account the impact of land use efficiency on the industrial structure [139], while ignoring the interaction of various influencing factors in the region. This paper is to use environmental regulations for land use. Land use efficiency has the responsibility of developing the local economy, and is also affected by heterogeneous environmental regulations. Adjusting land use efficiency, government intervention in resource allocation mainly through planning for land, whether the planning is reasonable or not, has a direct effect on the allocation of regional land resources. Through reasonable land planning, regional industries can be greenly transformed and industrial investment can be attracted at the same time[140], which is similar to the research results of Jin et al. At the same time, it also enhances the social responsibility of the region, and then transforms it into consumption power, and then acts on resource optimization to further promote the advanced development of regional industrial structure. However, it should also be noted that excessive planning and utilization of land resources in the region will break the balance with the environment and thus inhibit regional development. At present, some studies have the same way to influence the upgrading of industrial structure for the upgrading of industrial structure, which is based on the improvement of green technology innovation[141,142], and this paper adds the way of efficient land use to jointly promote the upgrading of industrial structure.

Under the background of continuous advocacy of green and sustainable development in the world[143], it is the general direction of industrial upgrading to focus on improving the level of industrial greening. Exploring the overall development of each country 's own industrial structure and changes in local environmental policies is an important issue that conforms to the current stage of seeking growth momentum conversion and future high-quality development[144]. Therefore, this paper starts from exploring the relevance of industrial structure upgrading between regions, grasping the development of regional environmental regulation and industrial

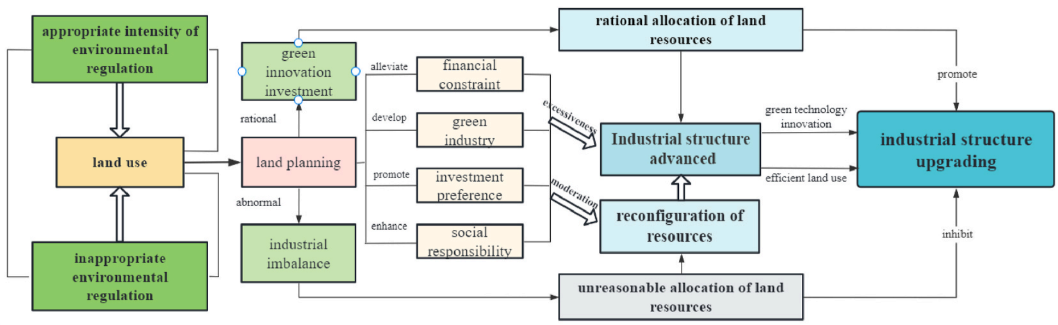

Fig. 8. The function mechanism of heterogeneous ER and LUE on ISU.

structure, and the closeness of regional land use efficiency to industrial structure upgrading. The three are unified into a whole for research, and the impact mechanism of environmental regulation and land use efficiency on industrial structure upgrading will play a role in the future[145]. Although there are many studies on industrial structure[146,147], but this paper believes that there is a lack of more accurate research and exploration in the future. Therefore, starting from the optimization of the research method model, the variables can be refined and the instability of the variables can be optimized. At the same time, the index system should be adjusted according to the actual development of the region, focusing more on the influencing factors of land use efficiency and environmental regulation on the industrial structure, so as to make an accurate contribution to the direction of government intervention and adjustment policies.

The research findings presented in this paper possess certain limitations and shortcomings. While the study delves into the examination of the industrial structure, incorporating both environmental regulation and land use efficiency from a dual perspective and amalgamating them into a cohesive framework, the utilization of spatial effect coupled with the threshold model allows for a more comprehensive analysis of the influencing factors on industrial structure. This, in turn, serves as a valuable reference for subsequent research endeavors directed towards the theoretical framework of industrial structure within the realms of land use and green development.

However, due to data and methodological constraints, further in-depth investigations are warranted. Firstly, the solitary reliance on the geographical distance matrix as the research matrix, based on the diversification of the weight matrix, may present limitations. Future research could explore empirical results under different matrices, such as economic matrices, geographical adjacency matrices, and comprehensive nested matrices. This approach aims to place greater emphasis on the establishment of influencing factors. Secondly, owing to the inertia and path dependence inherent in economic growth, the effects of the transformation of the economic development mode may become apparent only after a certain period. Therefore, the utilization of long-term dynamic samples for more detailed analysis and testing in the future is recommended to better capture the nuances of the economic transformation process.

6. Conclusion

This paper comprehensively considers the impact of ER LUE on the ISU, and establishes an analytical framework for the relationship between environmental regulation and land use efficiency，filling the gaps in current research on integrated analyses of LUE, ER and ISU. Considering the heterogeneity of ER, ER is divided into formal and informal environmental regulation, and the two are combined to form the same model to fully describe their impact on the “two modernizations” of industrial structure，improved research deficiencies in ER of heterogeneity. At the same time, considering the spillover effect of regional industrial structure upgrading, with the help of spatial Durbin model, the panel data analysis of 110 cities in the Yangtze River Economic Belt from 2000 to 2020 is used to test the “pollution paradise” hypothesis and the “innovation compensation” effect. Based on regional heterogeneity, this paper analyzes the impact of land use efficiency and environmental regulation on the upgrading of regional industrial structure, and further analyzes the “double threshold effect” of environmental regulation on the upgrading of industrial structure through land use efficiency through the threshold model, more in-depth exploration of the influence effects and factors, to complete the deeper influence limit study of ER on ISU. The main findings are as follows:

Firstly, the overall level of industrial rationalization and advancement in CYREB shows an upward trend. However, there are regional disparities in the rationalization and advancement of the industrial structure across different segments and cities. Industrial structure rationalization exhibits significant differentiation, with downstream regions such as Shanghai and Suzhou having average Regional Industrial Structure (RIS) levels of 432.05 and 374.22 respectively, while upstream regions have lower average RIS levels due to factors such as backward industrial facilities, limited transportation, sparse population, and others. In the middle reaches, there are fluctuations in certain years, possibly due to fluctuations in regional policies. Overall, weak environmental regulation in various regions leads to low LUE, resulting in inadequate rational allocation of industrial resources and imbalanced industrial structure rationalization. The process of industrial structure advancement shows a growing trend in the downstream region, while the middle and upstream regions exhibit a decreasing trend, mainly due to the increasing intensity of environmental regulation in the downstream region, which promotes higher LUE and the advancement of industrial structure. In the middle and downstream regions, environmental regulation shows a stable but low growth trend, resulting in weak rationalization of land resource utilization and less advanced industrial structure.

Secondly, formal environmental regulation significantly promotes local industrial structure rationalization and advancement, and also exhibits significant positive spillover effects on neighboring areas. However, the existence of pollution havens leads some enterprises to transfer high-pollution industries to neighboring provinces, weakening the role of environmental regulation in upgrading the industrial structure and resulting in low LUE. This hinders the rationalization and advancement of the industrial structure in neighboring areas, reflecting the general characteristics of “pollution havens”. Informal environmental regulation leads to a clear decline in the level of local industrial structure rationalization, as well as a decline in the rationalization and advancement of neighboring city’s industrial structure.

Secondly, FER profoundly propel the rationalization and progression of the local industrial structure, manifesting discernible positive spillover effects in proximate regions. Nonetheless, the existence of pollution havens prompts certain enterprises to relocate high-pollution industries to adjacent provinces, attenuating the efficacy of ER in elevating industrial structural integrity and yielding suboptimal LUE. This undermines the rationalization and progression of industrial structures in neighboring regions, encapsulating the prevalent attributes of “pollution havens.” IER precipitate a conspicuous regression in the degree of local industrial structure rationalization, concomitant with a downturn in the rationalization and progression of the industrial structure in proximal urban centers.

Thirdly, environmental regulation affects ISU through LUE, exhibiting a “double threshold effect” and a stage relationship of “strong inhibition - weak inhibition - interactive promotion”. When the threshold is less than 0.0315, environmental regulation is insufficient to compel local governments to improve LUE, resulting in the maintenance or deterioration of the existing land use status and hindering the upgrading of the industrial structure. When the threshold value is between 0.0315 and 0.0886, environmental regulation inhibits LUE and ISU, but the degree of inhibition gradually decreases. When the threshold value is greater than 0.0886, ER significantly increases enterprise pollution costs, compelling local governments to improve LUE through ISU. At this point, the “compensation effect” outweighs the “offsetting effect".

Considering the aforementioned impacts of environmental regulation on LUE and ISU, this paper suggests that when promoting green transformation in the context of economic development and industrial transfer at the national or regional level, tailored ER policies should be adopted based on local conditions. It is not advisable to continue implementing a “one-size-fits-all” approach. In the upstream, middle, and downstream regions, green transformation should be promoted in an orderly manner based on segmented resource endowments and industrial conditions. The intensity of environmental regulation should be adjusted accordingly, coordinating the gradient transfer of industries in the upstream, middle, and downstream regions. The promotion mechanisms for local government advancement should be adjusted to avoid resource misallocation caused by government investment. Furthermore, a better understanding of the hidden development costs of environmental pollution is crucial. Breaking the traditional paradigm of “pollution first, treatment later”, high-pollution industries should be forced to exit or transform into green industries. Encouraging environmental protection technological innovation and application by enterprises can help avoid formalism in ER policies. Additionally, the leverage effect of land use control between ER and ISU should be strengthened. Encouraging cities along the economic belt to reasonably allocate construction land indicators based on their own characteristics, understanding the double threshold effect of environmental regulation on LUE and ISU, and effectively promoting the combination of ER and land use can facilitate the upgrading of the manufacturing industry.

Data availability statement

The data is available from the corresponding author upon request.

CRediT authorship contribution statement

Hu Yu: Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Conceptualization. **Chaofan Zheng:** Writing – original draft, Visualization, Software, Methodology, Data curation, Conceptualization.

Declaration of competing interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled.

Acknowledgements

This work was supported by Key research and development project of Xinjiang Autonomous Region (2021B03002-2), National Natural Science Foundation of China (41701164).

Acknowledgements

The authors appreciate the valuable comments of editors.

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