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The nonlinear influence of innovation efficiency on carbon and haze co-control: the threshold effect of environmental decentralization

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Abstract

Environmental decentralization is an important prerequisite and institutional foundation for China's carbon and haze co-control. Prior research has answered the influence of environmental decentralization on carbon mitigation or haze control. Few studies have analyzed the influence of innovation efficiency on carbon and haze co-control in the context of environmental decentralization. Research on how to achieve the optimal allocation of environmental decentralization is rare. Based on an analysis of the dynamic evolution trends in China's carbon emissions, haze pollution, environmental decentralization, and innovation efficiency from 2006 to 2018 by exploiting kernel density estimation, this study examines the environmental decentralization threshold effect of innovation efficiency on carbon and haze co-control by employing dynamic threshold model and investigates reasonable allocation of environmental decentralization. The results revealed that, first, China's provincial carbon emissions and environmental decentralization performed an increasing trend. Haze pollution and innovation efficiency demonstrated a downward trend. Second, when environmental decentralization increases, the influence of innovation efficiency on carbon emissions presents a W-shape, whereas the influence of innovation efficiency on haze pollution follows an inverted N-shape. Third, there are remarkable heterogeneous environmental decentralization threshold effects on the influence of innovation efficiency on carbon and haze co-control. Fourth, appropriate environmental decentralization can enhance carbon and haze co-control effects of innovation efficiency. The central government entails appropriate empowerment of local governments in environmental administration and supervision authority but decreases the environmental monitoring authority of local governments.

Keywords Carbon and haze co-control · Environmental decentralization · Innovation efficiency · Nonlinear influence · Threshold effect

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1 Introduction

Global warming driven by carbon emissions and air pollution caused by haze pollution has emerged as a formidable global concern (Erdoğan et al., 2022). Carbon emissions and haze pollution bring a severe threat to human health and societal development. Storms, fogs, and floods, all of which are exacerbated by carbon emissions (Cetin & Sevik, 2016), have a severe influence on the safety of rail transport and aircraft flights (Chen et al., 2021). The number of patients with respiratory illnesses rises as a result of haze pollution (Cetin et al., 2019; Phung et al., 2016). Carbon emissions and haze pollution are primarily derived from fossil energy consumption, which is characterized by homology (Dahlkötter et al., 2010). Reducing carbon emissions can also lower haze pollution. Quantitative research on the synergistic management of carbon mitigation and haze control can save policy costs and improve decision-making efficiency. Consequently, investigating the synergistic management of carbon mitigation and haze control has significant guiding importance for global countries to achieve peak carbon emissions and air quality standards.

The relationship between economic development and environmental protection has emerged as a delicate and critical issue for academics and politicians. Environmental regulation has undoubtedly been an outstanding initiative to strengthen environmental protection in recent years (Jiang et al., 2021). According to the Porter Hypothesis, environmental regulation provides compliance cost effects and innovation compensation effects (Porter, 1991). The compliance cost effects are manifested by the fact that increasing the intensity of environmental regulation will squeeze out corporate investment in innovation and discourage innovation efficiency (Qiao et al., 2022). Corporations are expanding their pollution emissions in pursuit of profit maximization. The innovation compensation effects can be seen in the fact that enhanced environmental regulation stimulates corporate incentives to innovate, increases innovation investment, boosts innovation efficiency, compensates for regulatory costs, and achieves the goal of pollution reduction (Shao et al., 2020). Although numerous empirical studies by academics on the pollution reduction effects of environmental regulation have produced inconsistent conclusions, they essentially support the Porter Hypothesis. *Nevertheless, these researches are primarily grounded in the perspective of welfare economic theory, which presupposes that the government consistently pursues social welfare as its highest pursuit.* In contrast, public choice theory and environmental federalism are different from welfare economic theory. They discard the welfare government hypothesis and formulate the economic government hypothesis, suggesting that local governments are characterized by maximizing their interests (Oates, 2001). Incompatibility between behavioral preferences and environmental governance purposes in local government can frequently contribute to ineffective environmental regulation. *Environmental decentralization (ED)* is a critical factor in the alienation of local government behavior. As a result, academics have progressively turned their attention to the reduction effects of ED, forming diametrically contradictory conclusions (Lin & Xu, 2022). The negative school argued that ED distorts incentives and insufficiently constrains from central government, resulting in free-riding or unhealthy competition in environmental regulation by local governments and weakening pollution prevention performance (Cheng et al., 2020; Kunce & Shogren, 2007). On the one hand, environmental centralization can prevent local governments from undersupplying environmental public goods due to free-riding behavior and will effectively decrease the cost of environmental public goods. On the other hand, environmental centralization can discourage local governments from lowering environmental standards to induce more investment, employment, and tax revenue (Fredriksson

& Millimet, 2002). The positive school insisted that ED brings about orderly cooperation and competition among local governments and higher decentralization generates higher environmental standards, thus contributing to improved environmental quality (Lin & Xu, 2022; Sigman, 2014). Under an ED system, local governments can provide better environmental public services by adopting a cost-benefit analysis depending on the specific situation in their jurisdictions.

Prior research has provided beneficial references for this study. Nonetheless, some limitations in this research area need further improvement. First, existing theoretical and empirical research has not incorporated ED, innovation efficiency, and carbon and haze co-control into the same analytical framework. Although the literature has explored the influence of ED on environmental pollution, the potential mechanisms between them remain limited. Previous research has primarily concentrated on the nonlinear effects of environmental regulation on environmental pollution through innovation efficiency. Nevertheless, ED has given local governments greater discretionary power in environmental governance areas, which has a direct influence on environmental regulation. This indicates that ED may produce a nonlinear influence on carbon and haze co-control through innovation efficiency. Second, research on various ED, innovation efficiency, and the co-control of carbon and haze is scarce in published literature. ED is a complicated system, involving administration, supervision, and monitoring. The influence of various ED on carbon and haze co-control through innovation efficiency may be diverse. Third, the scientific and rational allocation of environmental management authority is the institutional foundation for consolidating the performance of environmental regulation to mitigate emissions. Nevertheless, little literature discussed how environmental management authority can be allocated optimally, especially environmental administration, supervision, and monitoring.

To fill these knowledge gaps, this study measures carbon emissions, haze pollution, ED, and innovation efficiency in China's provinces and investigates their dynamic evolution trends by employing kernel density estimation. On this basis, the nonlinear influence of innovation efficiency on carbon and haze co-control under different ED is examined by the dynamic threshold model. The optimal allocation of ED is explored based on the role of innovation efficiency in the co-control of carbon and haze under different levels of ED. Additionally, there are two reasons for selecting China as the research subject in this study. First, China is a serious emitter of carbon emissions and haze pollution. Simultaneously, China is a significant participant and contributor to carbon and haze co-control. Research on the relationship between ED, innovation efficiency, and co-control of carbon and haze in China has an exemplary effect. Second, although China has not established an ED system earlier, it has a relatively comprehensive system of ED. Data are complete and easily accessible.

In comparison with previous literature, the contributions of this study are in three aspects. First, this study theoretically and empirically integrates ED, innovation efficiency, and the co-control of carbon and haze into the same research framework. Second, this study explores the influence of innovation efficiency on carbon and haze co-control by developing the dynamic threshold model that uses heterogeneous ED as threshold variables. Third, this study investigates the optimal allocation of heterogeneous ED by examining the role of innovation efficiency on carbon and haze co-control at different levels of heterogeneous ED.

The remainder of this study is divided into five sections. Section 2 explains the theoretical analysis and hypotheses. Section 3 introduces an overview of the methodology and data. Section 4 analyzes the empirical results. Section 5 highlights the discussion. Section 6 summarizes the conclusions and implications.

2 Theoretical analysis and hypotheses

2.1 Environmental decentralization

The environmental federalism theory suggests that clarifying the authority and responsibility relationship between the central and local governments in environmental governance and the rational allocation of environmental protection functions at various governments is a critical initiative to address the environmental pollution issue (Fredriksson & Wollscheid, 2014). Nevertheless, the influence of ED on innovation efficiency exhibits nonlinearity, thus exacerbating environmental governance complications. ED may enhance innovation efficiency to discourage environmental pollution. First, ED identifies local governments' responsibilities in the environmental governance process, facilitating local governments to provide more efficient and strict environmental management policies and instruments with the advantage of information, and driving innovation efficiency in corporations (Zou et al., 2019). Second, ED enhances the incentives for local governments to engage in research and development (R&D). Government R&D expenditure compensates for the cost expenditure of corporations in implementing innovation activities, increasing innovation investment, reducing innovation risks, and improving innovation efficiency (Lin & Xu, 2022). In contrast, ED may decrease innovation efficiency and exacerbate environmental pollution. First, ED may become an instrument for local governments to develop their economies. To encourage more capital to move in, local governments have decreased environmental protection standards, creating bottom-up competition and making it difficult to drive improvements in regional innovation efficiency. Second, promotion tournaments provide incentives for local governments to orient policy resources toward their performance (Pu & Fu, 2018). The production sector, with low risk, high returns, and short payback periods, has emerged as a favored area for significant resource investment, while the technology sector, with high risk, low returns, and long payback periods, has become a forbidden place for resource investment (Cole et al., 2006). Hence, Hypothesis 1 is formulated.

Hypothesis 1 Innovation efficiency has the ED threshold effect on the co-control of carbon and haze.

2.2 Environmental administration decentralization

Environmental administration decentralization (EAD) involves developing environmental administration systems and rationalizing environmental governance investments and staffing structures (Wu et al., 2020a, 2020b). It empowers local governments with greater independence in investment and staffing for environmental pollution management and more flexibility in restructuring environmental investments. This enables the scale and structure of corporate innovation investment to be optimized, promoting improvements in innovation efficiency. With the increasing EAD, local officials gradually loosen the regulation of high-pollution and high-tax corporations by adjusting the environmental protection investment structure and personnel structure with the environmental administration authority (Konisky, 2007). In contrast, environmental regulatory pressure is transferred to low-pollution and low-tax corporations. The effectiveness of local environmental governance investment and staffing efficiency is greatly diminished, which is not conducive to innovation efficiency. Hence, Hypothesis 2 is formulated.

Hypothesis 2 Innovation efficiency has an EAD threshold effect on the co-control of carbon and haze.

2.3 Environmental supervision decentralization

Environmental supervision decentralization (ESD) confers greater autonomy on local governments in establishing environmental management and supervision systems, implementing emission charge auditing tasks, and environmental enforcement (Karp & Rezai, 2014). Emission charge audits and environmental enforcement by local governments force corporations to accelerate innovation to compensate for compliance costs (Wu et al., 2020a, 2020b). Nevertheless, inappropriate ESD can induce local governments to relax their efforts to emissions charging audits in high-pollution and high-tax corporations. Corporations frequently prefer to discontinue their environmental pollution control facilities to reduce their operating costs, rather than to accelerate their innovation efficiency (Farzanegan & Mennel, 2012). It reduces the effectiveness of ESD in pollution control. Hence, Hypothesis 3 is formulated.

Hypothesis 3 Innovation efficiency has an ESD threshold effect on the co-control of carbon and haze.

2.4 Environmental monitoring decentralization

Environmental monitoring decentralization (EMD) signifies that local governments possess increased authority to self-evaluate the environmental situation in their jurisdictions (Wu et al., 2020a, 2020b) Local governments can expeditiously collect and evaluate environmental pollution data, and urge corporations to precisely adjust their innovation resource allocation and enhance their innovation efficiency according to the evaluation results. Nevertheless, EMD may generate issues of modification or concealment in monitoring data, rendering officially published environmental monitoring data at variance with social monitoring data. This prevents corporations from making accurate and effective judgments about environmental pollution management, causing an imbalance in innovation resource allocation and even exacerbating negative environmental externalities for corporations (Lipscomb & Mobarak, 2017). Hence, Hypothesis 4 is formulated.

Hypothesis 4 Innovation efficiency has an EMD threshold effect on the co-control of carbon and haze.

3 Methodology and data

3.1 Model setting

3.1.1 Kernel Density Estimation

This study uses the kernel density estimation proposed by Rosenblatt (1956) to investigate the dynamic evolution trends of China's provincial carbon emissions, haze pollution, ED, and innovation efficiency. Kernel density estimation does not make any constraining assumptions for the premise assumptions set by the model and can effectively avoid the statistical inference deviation between the real and estimated values produced by the model set (Linton & Xiao, 2019). Its functional form is shown in formula (1).

$$f(x_0) = \frac{1}{nh}\sum_{i=1}^{n} K\left(\frac{x_i - x_0}{h}\right) \tag{1}$$

where n represents the observed value. h means smoothing parameter. $K\left(\frac{x_i - x_0}{h}\right)$ is the kernel function. This study selects the *Gaussian* as a kernel function due to the diversity of kernel functions. Its expression is as follows.

$$K(z) = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{z^2}{2}\right) \tag{2}$$

3.1.2 Dynamic threshold model

Based on the previous analysis, the threshold model proposed by Hansen (1999) is adopted to examine the ED threshold effect of innovation efficiency on carbon and haze co-control. The threshold model both accurately identifies the nonlinear threshold effects between the explanatory and explanatory variables, and provides an estimate and test of the threshold size and its authenticity. Formula (3) is the basic threshold model.

$$Y_{it} = \beta_0 + \beta_1 X_{it} \cdot I(q_{it} \le z) + \beta_2 X_{it} \cdot I(q_{it} > z) + \mu_{it} + \varepsilon_{it} \tag{3}$$

where Y_{it} and X_{it} denote the explained variable and the explanatory variable, respectively. $I(\bullet)$ means the indicator function. q_{it} represents the threshold variable. z indicates the estimated threshold. μ_{it} is the individual-specific effect. ε_{it} is the random interference item.

The discharge process of pollutants is dynamic (Acheampong, 2018). Consequently, this study extends the static threshold model and constructs the dynamic threshold model by following the method of Dang et al. (2012). In contrast to the static threshold model, the dynamic threshold model has two advantages. First, it can determine the threshold endogenously based on the characteristics of the constraint variable (Wu et al., 2020a, 2020b). Second, it deals with potential endogenous impacts (Wu et al., 2019). The dynamic threshold model is shown as follows.

$$\begin{aligned} PL_{it} &= \beta_0 + \beta PL_{it-1} + \beta_1 IE_{it} \bullet I\left(ED_{it} \le z_1\right) + \beta_2 IE_{it} \bullet I\left(z_1 < ED_{it} \le z_2\right) \\ &\quad + \beta_n IE_{it} \bullet I\left(z_{n-1} < ED_{it} \le z_n\right) + \mu_{it} + \varepsilon_{it} \end{aligned} \tag{4}$$

where PL_{it} denotes carbon emissions or haze pollution. PL_{it-1} indicates the first lag period of carbon emissions or haze pollution. IE_{it} and ED_{it} represent innovation efficiency and environmental decentralization, respectively. Other parameters are consistent with the static threshold model.

3.2 Data description

3.2.1 Dependent variable

Carbon emissions (CE) This study estimates carbon emissions following the method of Shen et al. (2021). The calculation formula is presented in formula (5).

$$\mathrm{CE} = \sum_i \mathrm{CE}_i = \sum_i e_i \times f_i \times \rho_i \times \delta_i \times \frac{44}{12} \tag{5}$$

where i indicates fossil energy, $i = 1, 2, 3 \ldots 8$, including coal, oil, diesel, etc. e_i denotes the consumption of energy i. f_i represents the conversion coefficient of energy i. ρ_i means the carbon coefficients of energy i. δ_i is the oxidation rate of energy i. Specific parameter selection is based on *the 2006 IPCC Guidelines for National Greenhouse Gas Inventory*.

Haze pollution Haze pollution is represented by PM2.5 concentration, which is produced by *Dalhousie University Atmospheric Composition Analysis Group* and abbreviated as *PM*. According to this database, this study using *ArcG*IS calculates the yearly average PM2.5 concentration in China's provinces from 2006 to 2018.

3.2.2 Explanatory variables

Innovation efficiency (IE) This study employs data envelopment analysis (DEA) to estimate China's provincial innovation efficiency. DEA has its unique advantages in measuring multiple inputs and outputs efficiency and is a common approach to measuring efficiency because of its superiority in avoiding production function misspecification and relative objectivity (Long, 2021). The specific measurement steps are as follows.

It is assumed that there are n units and each unit has m types of input vectors and s types of output vectors. For any unit, the model for determining its effectiveness can be expressed as formula (6).

$$\min_{\theta,\lambda} \left[\theta - \varepsilon\left(e^t s^- + e^t s^+\right)\right], s.t. \begin{cases} \sum\limits_{i-1}^{n} \lambda_i x_{ij} + s^- = \theta x^{0j} \\ \sum\limits_{i-1}^{n} \lambda_i y_{ir} - s^+ = y_{0r} \\ \sum\limits_{i=1}^{n} \lambda_i = 1 \\ \lambda_i \geq 0; s^+ \geq 0; s^- \geq 0 \end{cases} \tag{6}$$

where $i = 1, 2, 3, \ldots, n$; $j = 1, 2, 3, \ldots, m$; $r = 1, 2, 3, \ldots, s$; $x_{ij}(j = 1, 2, 3, \ldots, m)$ denotes the j-th input factor of the i-th unit. $y_{ir}(r = 1, 2, 3 ..., s)$ indicates the s-th input factor of the i-th unit. θ indicates the valid value of the unit. s^+ and s^- represent input redundancy and output deficiencies in units, respectively.

There are no unified criteria for selecting innovation efficiency variables in academia. Following the research of Lv et al. (2021), this study selects internal expenditure of R&D funding and the full-time equivalent of R&D personnel as input variables and regional GDP as an output variable.

3.2.3 Threshold variables

Environmental decentralization (ED) The accurate measurement of this variable is the key to solving the problem to be studied. Nevertheless, an extremely difficult question is how to accurately measure ED. First, there are significant differences in environmental management systems of different countries, including systems and structures. How to accommodate these differences is extremely complicated and challenging (Luo et al., 2019). Second, policies between government departments are interactive, there may be errors in using policy implementation effects to measure ED (Elheddad et al., 2020). Third, due to the overlapping responsibilities of various government departments in operation, the measurement of ED is more complicated (Habans et al., 2019). Based on the research of (Wu et al., 2020a, 2020b), this study employs the distribution of employees in the environmental protection system to characterize ED. Given the detailed division of environmental management systems in China, ED is further subdivided into three aspects, including administration, supervision, and monitoring, to explore the ED threshold effects of innovation efficiency on carbon and haze co-control. Additionally, the regional economic scale can potentially affect the number of local environmental practitioners. This study adopts the economic reduction factor to deflate the ED and reduce the endogenous interference. The specific expressions are shown in formulas (7–10).

$$\mathrm{ED}_{it} = \left[\frac{\mathrm{RE}_{it}/\mathrm{RP}_{it}}{\mathrm{NE}_{t}/\mathrm{NP}_{t}}\right] \times \left[1 - \left(\mathrm{CDP}_{it}/\mathrm{CDP}_{t}\right)\right] \tag{7}$$

$$\mathrm{EAD}_{it} = \left[\frac{\mathrm{RAE}_{it}/\mathrm{RP}_{it}}{\mathrm{NAE}_{t}/\mathrm{NP}_{t}}\right] \times \left[1 - \left(\mathrm{CDP}_{it}/\mathrm{CDP}_{t}\right)\right] \tag{8}$$

$$\mathrm{ESD}_{it} = \left[\frac{\mathrm{RSE}_{it}/\mathrm{RP}_{it}}{\mathrm{NSE}_{t}/\mathrm{NP}_{t}}\right] \times \left[1 - \left(\mathrm{CDP}_{it}/\mathrm{CDP}_{t}\right)\right] \tag{9}$$

$$\mathrm{EMD}_{it} = \left[\frac{\mathrm{RME}_{it}/\mathrm{RP}_{it}}{\mathrm{NME}_{t}/\mathrm{NP}_{t}}\right] \times \left[1 - \left(\mathrm{CDP}_{it}/\mathrm{CDP}_{t}\right)\right] \tag{10}$$

where RE_{it}, RAE_{it}, RSE_{it}, RME_{it} represent the number of environmental protection personnel, administration personnel, supervision personnel, and monitoring personnel in the region i during the period t, respectively. NE_{t}, NAE_{t}, NSE_{t}, NME_{t}, respectively, denote the number of environmental protection personnel, administrative personnel, supervision personnel, and monitoring personnel in the nation during the period t. CDP_{it} and CDP_{t} represent the gross domestic product in the region i and the national gross domestic product during the period t, respectively.

3.2.4 Control variables

Regional carbon emissions and haze pollution are driven by many factors. Following the research of Udemba (2019), control variables are selected as follows. (1) Government size (GOS) expresses the ratio of government expenditure to GDP. (2) Environmental governance (ENG) denotes the ratio of environmental governance investment in GDP. (3) R&D investment (RDI) represents the ratio of R&D investment in GDP. (4) Technology market turnover ratio (TMT) indicates the ratio of technology market turnover in GDP. (5) Urbanization rate (UR) is measured by the percentage of the permanent population. (6) Industrial structure (IS) is indicated by the percentage of the secondary industry. (7) Energy structure (ES) is expressed by the ratio of coal consumption. (8) Foreign trade (FT), which is present by the ratio of total imports to GDP. (9) Foreign direct investment (FDI), which is denoted by the ratio of total foreign investment in GDP. To ensure data integrity and availability, the research objects select 30 Chinese provinces. The data are collected from *the National Bureau of Statistics* and *Environmental Statistics Yearbook*. All variables have been processed by logarithm to solve the heteroscedasticity of the model. Table 1 reports statistical characteristics of variables.

4 Results

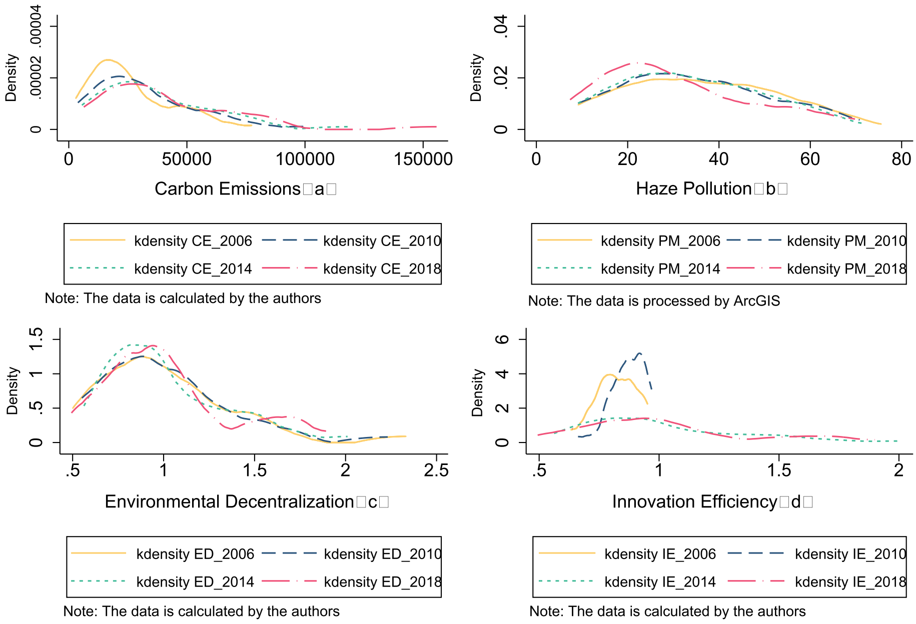
4.1 Dynamic evolution trend

Figure 1 describes the dynamic evolution trends of China's provincial carbon emissions, haze pollution, ED, and innovation efficiency.

From the perspective of the curve position translation, the carbon emission curve displays a rightward shift, indicating that carbon emissions are continuing to grow in China's provinces. The haze pollution curve demonstrates a leftward shift, denoting an improvement in haze pollution in China's provinces. The ED curve has experienced a shift from leftward to rightward, reflecting the developing trend of ED in China from low to high. The innovation efficiency curve shifts from right to left, illustrating that innovation efficiency in China's provinces exhibits a fluctuating state of increasing and then decreasing.

Table 1 Statistical characteristics of each variable

Variables	Obs	Mean	Std. dev.	Min	Max
CE	390	10.235	0.705	8.013	11.956
PM	390	3.380	0.549	1.938	4.404
IE	390	− 0.219	0.181	− 0.984	− 0.025
GOS	390	− 1.548	0.390	− 2.437	− 0.467
ENG	390	− 4.394	0.482	− 5.812	− 3.163
RDI	390	− 4.838	0.616	− 7.586	− 3.822
TMT	390	− 5.430	1.328	− 8.670	− 1.811
UR	390	− 0.631	0.235	− 1.264	− 0.110
IS	390	− 0.803	0.219	− 1.680	− 0.527
ES	390	− 0.463	0.396	− 2.982	− 0.030
FT	390	− 3.176	1.856	− 9.091	0.078
FDI	390	− 1.413	0.869	− 3.464	1.657
ED	390	− 0.040	0.324	− 0.706	0.855
EAD	390	− 0.059	0.329	− 0.964	0.744
ESD	390	− 0.072	0.313	− 0.808	0.928
EMD	390	− 0.185	0.519	− 1.783	0.909



Note: The data is calculated by the authors

Note: The data is processed by ArcGIS

Note: The data is calculated by the authors

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Fig. 1 The kernel density estimation of CE, PM, ED, and IE

From the perspective of the curve peak shape, the peak shapes of the carbon emission curve, the haze pollution curve, and the ED curve are presented as single peaks. With multiple prominences on the right side of the peak, their curves have multiple prominences on the right side of the peak. These characteristics represent the weak polarization of carbon emissions, haze pollution, and ED in China's provinces. Nevertheless, this phenomenon is not so obvious. The peak shape of innovation efficiency is double-peaked, suggesting that the polarization of innovation efficiency in China's provinces is significant, and shows the characteristics of high-level agglomeration and low-level convergence.

From the perspective of the curve peak change, the peak of the carbon emission curve has turned from steep to flat, indicating that China's provincial carbon emissions have a Matthew effect, and the spatial gap is gradually widening. The peak of the haze pollution curve has changed from flat to steep, representing that the spatial difference of haze pollution in China's provinces is shrinking. The peak of the ED curve undergoes the process of flat, steep, and flat, which implies that the spatial gap in ED in China's provinces exhibits a trend of increasing, decreasing, and increasing. The peak of the innovation efficiency curve presents a changing trend from steep to flat, reflecting a moderating spatial gap in inter-provincial innovation efficiency in China at the early stages of development. Nevertheless, the gap in innovation efficiency between different provinces gradually expanded after 2014.

4.2 Unit root test

As macroeconomic variables are usually nonstationary, the stability must be tested before regression analysis. The methods of Levin-Lin-Chu (LLC) and Im-Pesaran-Shin (IPS) are

Table 2 Unit root test

Original value	LLC	IPS	Difference value	LLC	IPS	Conclusion
CE	-9.136^{***}	-3.561^{***}	D_CE	-11.278^{***}	-7.491^{***}	Stability
PM	-6.162^{***}	-6.170^{***}	D_PM	-9.908^{***}	-9.743^{***}	Stability
IE	-4.112^{***}	-1.652^{**}	D_IE	-9.931^{***}	-5.065^{***}	Stability
ED	-6.643^{***}	-5.840^{***}	D_ED	-11.407^{***}	-8.101^{***}	Stability
GOS	-6.344^{***}	-2.070^{**}	D_GOS	-8.845^{***}	-7.193^{***}	Stability
ENG	-9.970^{***}	-4.965^{***}	D_ENG	-9.936^{***}	-8.394^{***}	Stability
RDI	-5.883^{***}	0.834	D_RDI	-5.347^{***}	-5.598^{***}	Stability
TMT	-2.423^{***}	-1.746^{**}	D_TMT	-9.461^{***}	-8.125^{***}	Stability
UR	-11.732^{***}	-2.530^{***}	D_UR	-20.693^{***}	-6.564^{***}	Stability
IS	-4.127^{***}	0.358	D_IS	-8.876^{***}	-6.379^{***}	Stability
ES	-5.753^{***}	-2.272^{**}	D_ES	-15.772^{***}	-7.231^{***}	Stability
FT	-5.271^{***}	-3.291^{***}	D_FT	-6.066^{***}	-8.372^{***}	Stability
FDI	-1.626^{**}	-0.567	D_FDI	-3.179^{***}	-7.855^{***}	Stability
EAD	-9.009^{***}	-3.986^{***}	D_EAD	-25.801^{***}	-7.446^{***}	Stability
ESD	-9.095^{***}	-5.077^{***}	D_ESD	-10.566^{***}	-7.981^{***}	Stability
EMD	-7.881^{***}	-5.323^{***}	D_EMD	-10.733^{***}	-5.077^{***}	Stability

$^{*}p<0.1$, $^{**}p<0.05$, $^{***}p<0.01$

commonly used to test the stability of variables (Im et al., 2003; Levin et al., 2002). The former is suitable for the same root, and the latter is suitable for different roots. This study uses the LLC and IPS methods to verify the stability of the variables. Table 2 demonstrates the test results in the original value and difference value of each variable under the LLC and IPS methods. From the perspective of the original value, all variables pass the test of the LLC method. RDI, IS, FDI fail to satisfy the IPS method test. Nevertheless, the difference value of each variable all passed the LLC and IPS tests at the 1% significance level, which means that the series data corresponding to all cross sections are stationary series.

4.3 Dynamic threshold effects of environmental decentralization

4.3.1 Carbon emissions

Taking carbon emissions as a dependent variable and ED as a threshold variable, the tests of significance and regression are demonstrated in Tables 3 and 4. Results from Tables 3 and 4 illustrate that ED has a triple threshold effect. When ED is lower than the first threshold ($ED \leq -0.490$, $P < 0.01$), a significantly negative relationship exists between innovation efficiency and carbon emissions ($\beta_1 = -0.683$, $P < 0.05$), which means that the low level of ED improves innovation efficiency and effectively curbed carbon emissions. When ED locates between the first threshold and the second threshold ($-0.490 < ED \leq -0.216$, $P < 0.05$), the influence of innovation efficiency and carbon emissions has changed significantly, which reports that the inhibitory effect of innovation efficiency on carbon emissions has been transformed into a promoting effect under the influence of ED. Innovation efficiency is positively associated with carbon emissions ($\beta_2 = 0.182$, $P < 0.05$). When ED reports between the second threshold and

Table 3 The results of the threshold significance test

Parameter	Categories		CE	PM
Threshold	Single threshold		– 0.490***	0.063**
	Double threshold		– 0.216**	0.117***
	Triple threshold		0.090**	0.231*
F statistics	Single threshold		39.318	17.440
	Double threshold		25.972	32.251
	Triple threshold		33.397	13.062
The critical value	Single threshold	1%	36.547	24.062
		5%	23.905	15.434
		10%	16.324	10.819
	Double threshold	1%	35.916	22.751
		5%	21.991	14.338
		10%	12.526	10.922
	Triple threshold	1%	46.544	29.175
		5%	24.383	18.423
		10%	15.954	12.223
Bootstrap			400	400
Results			Triple threshold	Triple threshold

***$p<0.01$, **$p<0.05$, *$p<0.1$

the third threshold ($-0.216 < \mathrm{ED} \leq 0.090$, $P < 0.05$), innovation efficiency presents a significantly negative relationship with carbon emissions ($\beta_3 = -0.303$, $P < 0.01$), which denotes that innovation efficiency has a positive effect on carbon emission reduction, but this positive effect on emission reduction is weakened ($|\beta_1| > |\beta_3|$). When ED exceeds the third threshold ($\mathrm{ED} > 0.090$, $P < 0.05$), there is a positive relationship between innovation efficiency and carbon emissions ($\beta_4 = 0.175$, $P < 0.05$), which indicates that high-intensity ED has caused a loss of innovation efficiency, which is not conducive to carbon reduction. Similarly, the positive effect of carbon emissions is weakened ($\beta_2 > \beta_4$). It can be observed that the correlation between innovation efficiency and carbon emissions is not monotonous under the effect of ED. With the broadening of ED, the relationship between innovation efficiency and carbon emissions presents a W-shape.

4.3.2 Haze pollution

Tables 3 and 4 also report the significance test and regression results with haze pollution as a dependent variable and ED as a threshold variable. As indicated in Tables 3 and 4, the triple threshold effect is consistent with carbon emissions. When the level of ED is sufficiently low ($\mathrm{ED} \leq 0.063$, $P < 0.05$), the regression coefficient of innovation efficiency fails the significance test at the level of 5% ($\beta_1 = -0.203$, $P < 0.01$). With the increases in the level of ED ($0.063 < \mathrm{ED} \leq 0.117$, $P < 0.01$), the regression coefficient of innovation efficiency changes from negative to positive ($\beta_2 = 0.175$, ($P < 0.05$)), which means that innovation efficiency promotes haze pollution at this level of ED. Nevertheless, there is a positive connection between innovation efficiency and haze pollution control ($\beta_3 = -0.458$,

Table 4 The estimation results of the dynamic threshold model

Parameter		CE	PM
IE	$ED \leq -0.490$	-0.683^{***} (-5.70)	
	$-0.490 < ED \leq -0.216$	0.182^{**} (2.00)	
	$-0.216 < ED \leq 0.090$	-0.303^{***} (-4.17)	
	$ED > 0.090$	0.175^{**} (2.57)	
	$ED \leq 0.063$		-0.203^{***} (-3.18)
	$0.063 < ED \leq 0.117$		0.175^{**} (2.13)
	$0.117 < ED \leq 0.231$		-0.458^{***} (-6.40)
	$ED > 0.231$		-0.215^{***} (-3.06)
L.CE		0.349^{***} (4.05)	
L.PM			0.524^{***} (13.32)
GOS ep		0.611^{***} (8.78)	0.141^{**} (2.20)
ENG dwt		0.023 (1.32)	0.034^{**} (2.17)
RDI drd		0.001 (0.02)	-0.139^{***} (-3.80)
TMT dtm		-0.024^{*} (1.95)	-0.032^{**} (-2.91)
UR		1.121^{***} (9.46)	-0.545^{***} (-5.18)
IS		0.277^{***} (3.72)	-0.097 (-1.46)
ES		0.076^{**} (2.10)	0.064^{**} (1.96)
FT dei		-0.002 (-0.22)	-0.012 (-1.24)
FDI dfdi		-0.016 (-0.79)	-0.037^{**} (-1.96)
Cons		12.065^{***} (61.66)	2.383^{***} (13.13)
R^2		0.751	0.622

The T-statistic is presented in parentheses

$^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$

$P < 0.01$), when the ED crossed a certain level ($0.117 < ED \leq 0.231$), which indicates that the innovation efficiency at this time enhances haze pollution control. When the level of ED is higher than the third threshold ($ED > 0.231$, $P < 0.10$), innovation efficiency performs an inhibitory effect on haze pollution ($\beta_4 = -0.215$, $P < 0.01$). In contrast to carbon emissions, the relationship between innovation efficiency and haze pollution is expressed as an inverted N-shape.

In summary, there are significant differences in the role of innovation efficiency on carbon and haze reduction under different levels of ED. This demonstrates the existence of environmental decentralization threshold effects of innovation efficiency on carbon and haze co-control. Hypothesis 1 is proved.

4.3.3 Authenticity test

Following the threshold significance test, it is necessary to further use the likelihood ratio function to test the true value of the dynamic threshold effect. According to Table 3 and Fig. 2, with carbon emissions as the dependent variable, the LR value of the 95% confidence interval of the triple threshold estimate has passed the significance test at the level of 5%, which can be concluded the threshold estimate passed the authenticity test.

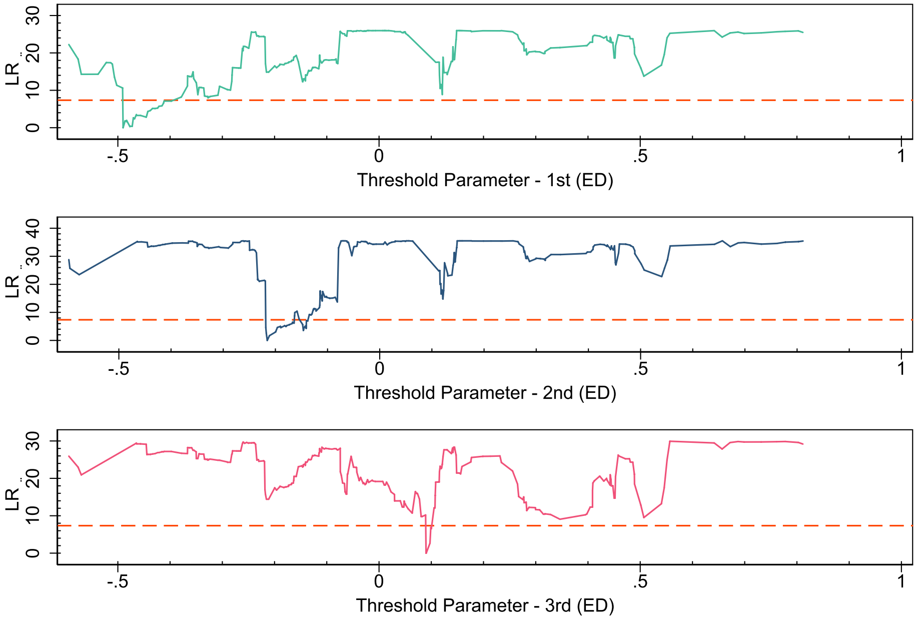

Fig. 2 Authenticity test based on ED (carbon emission is the dependent variable)

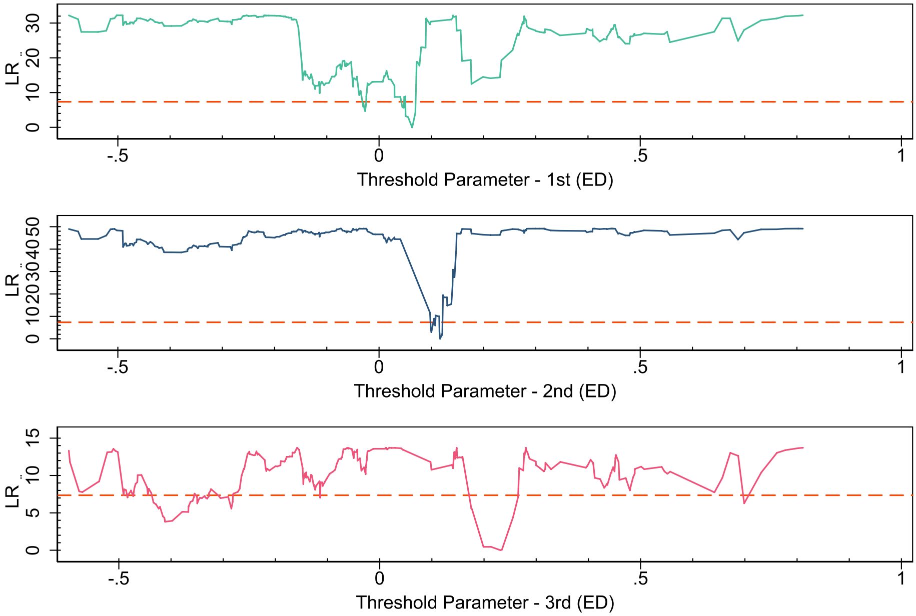

Fig. 3 Authenticity test based on ED (haze pollution is the dependent variable)

Similarly, based on Table 3 and Fig. 3, the LR value of the 95% confidence interval of the triple threshold estimate is significant in haze pollution as the dependent variable. Consequently, it can be reported that the estimated value of the triple threshold is equal to its true value. In summary, the threshold value estimation is effective and robust.

4.4 Dynamic threshold effects of heterogeneous environmental decentralization

This study further examines the influence of innovation efficiency on carbon and haze co-control under the heterogeneous ED from administration, supervision, and monitoring.

4.4.1 Environmental administrative decentralization

Table 5 describes that EAD has double threshold values. Table 6 reports the EAD threshold effects of innovation efficiency on carbon and haze co-control. In terms of carbon emissions, low-level EAD enhances the negative effect of innovation efficiency on carbon emissions ($\mathrm{EAD} \leq 0.046$, $\beta = -0.238$, $P < 0.01$). The positive effect of innovation efficiency on carbon emission is not significant at the high level of EAD ($\mathrm{EAD} > 0.317$, $\beta = 0.010$). When EAD is between the first and second threshold, innovation efficiency promotes the growth of carbon emissions ($-0.238 < \mathrm{ED} \leq 0.317$, $\beta = 0.467$, $P < 0.01$). In terms of haze pollution, appropriate EAD enables innovation efficiency to effectively control haze

Table 5 The results of the threshold significance test

Parameter	Categories		EAD		ESD		EMD	
			(1)	(2)	(3)	(4)	(5)	(6)
			CE	PM	CE	PM	CE	PM
Threshold	Single threshold		0.046^{***}	-0.270^{***}	-0.697^{**}	-0.090^{***}	-0.281^{***}	0.092^{***}
	Double threshold		0.317^{**}	0.469^{**}	-0.544^{**}	-0.023^{**}	–	0.122^{**}
	Triple threshold		–	–	0.139^{**}	0.121^{*}	–	0.158^{**}
F statistics	Single threshold		54.601	33.368	37.665	32.867	31.718	21.079
	Double threshold		39.809	10.742	17.701	16.653	–	14.349
	Triple threshold		–	–	24.286	8.770	–	9.431
The critical value	Single threshold	1%	34.979	23.992	45.108	22.736	42.855	21.079
		5%	17.562	14.281	28.151	15.439	26.396	14.349
		10%	12.706	10.664	18.991	11.037	16.799	9.431
	Double threshold	1%	29.123	11.750	36.553	33.923	–	20.821
		5%	15.068	6.158	20.025	16.063	–	11.654
		10%	11.110	2.967	13.998	11.563	–	8.383
	Triple threshold	1%		–	30.466	18.282	–	21.441
		5%	–	–	17.799	11.300	–	13.642
		10%	–	–	12.708	8.001	–	8.745
Bootstrap			400	400	400	400	400	400
Results			Double	Double	Triple	Triple	Single	Triple

$^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$

Table 6 Estimation results of the heterogeneous environmental decentralization threshold model

	EAD		ESD		EMD	
	CE	PM	CE	PM	CE	PM
	(1)	(2)	(3)	(4)	(5)	(6)
IE	-0.238^{***}					
$\text{EAD} \le 0.046$	(-3.40)					
IE	0.467^{***}					
$0.046 < \text{EAD} \le 0.317$	(5.62)					
IE	0.010					
$\text{EAD} > 0.317$	(0.15)					
IE		-0.043				
$\text{EAD} \le -0.270$		(-0.51)				
IE		-0.325^{***}				
$-0.270 < \text{EAD} \le 0.469$		(-5.63)				
IE		0.067				
$\text{EAD} > 0.469$		(0.85)				
IE			-0.634^{***}			
$\text{ESD} \le -0.697$			(-4.59)			
IE			0.024			
$-0.697 < \text{ESD} \le -0.544$			(0.27)			
IE			-0.414^{***}			
$-0.544 < \text{ESD} \le 0.139$			(-5.20)			
IE			0.149^{**}			
$\text{ESD} > 0.139$			(2.00)			
IE				-0.083		
$\text{ESD} \le -0.090$				(-1.34)		
IE				-0.370^{***}		
$-0.090 < \text{ESD} \le -0.023$				(-3.27)		
IE				-0.750^{***}		
$-0.023 < \text{ESD} \le 0.121$				(-7.46)		
IE				-0.279^{***}		
$\text{ESD} > 0.121$				(-4.23)		
IE					-0.475^{***}	
$\text{EMD} \le -0.281$					(-4.68)	
IE					0.030	
$\text{EMD} > -0.281$					(0.047)	
IE						-0.222^{***}
$\text{EMD} \le 0.092$						(-3.76)
IE						-0.004
$0.092 < \text{EMD} \le 0.122$						(-0.06)
IE						-0.582^{***}
$0.122 < \text{EMD} \le 0.158$						(-7.08)
IE						-0.303^{***}
$\text{EMD} > 0.158$						(-4.41)
L.CE	0.314^{***}		0.308^{***}		0.295^{***}	
	(3.62)		(3.49)		(3.13)	

Table 6 (continued)

	EAD		ESD		EMD	
	CE	PM	CE	PM	CE	PM
	(1)	(2)	(3)	(4)	(5)	(6)
L.PM		0.523^{***}		0.519^{***}		0.536^{***}
		(12.97)		(13.10)		(0.040)
Cons	11.639^{***}	2.442^{***}	11.855^{***}	2.645^{***}	11.754^{***}	2.694^{***}
	(59.73)	(13.20)	(59.64)	(14.72)	(55.99)	(15.28)
Control	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.747	0.600	0.738	0.617	0.698	0.616

The T-statistic is presented in parentheses

$^{***}p<0.01$, $^{**}p<0.05$, $^{*}p<0.1$

pollution ($-0.270 < \text{EAD} \le 0.469$, $\beta = -0.325$, $P < 0.01$). When EAD is higher than the second threshold and lower than the first threshold ($\text{EAD} \le -0.270$, $\text{EAD} > 0.469$), the influence of innovation efficiency on haze pollution is not significant. In summary, innovation efficiency contributes positively to carbon and haze co-control at an appropriate level of EAD. Hypothesis 2 is verified.

4.4.2 Environmental supervision decentralization

Table 6 also illustrates the ESD threshold effects of innovation efficiency on carbon and haze co-control. Columns (3) and (4) from Table 5 demonstrate that ESD has a triple threshold. Specifically, as shown in column (3), when ESD is below the first threshold and between the second and third thresholds ($\text{ESD} \le -0.697$, $-0.544 < \text{ESD} \le 0.139$), innovation efficiency indicates a significant negative relationship with carbon emissions ($\beta_1 = -0.634$, $\beta_3 = -0.414$). In addition, innovation efficiency has a stronger positive effect on carbon emission reduction at low-level ESD ($|\beta_1| > |\beta_3|$). Under other levels of ESD, the regression coefficient of innovation efficiency is positive. As provided in columns (4), when ESD crosses the single threshold ($\text{ESD} > -0.090$), innovation efficiency is conducive to haze pollution control. There is a reverse relationship between innovation efficiency and haze pollution. In summary, innovation efficiency has positive effects on carbon and haze reduction under an appropriate level of ESD. Hypothesis 3 is verified.

4.4.3 Environmental monitoring decentralization

Table 5 reports the EMD has a single threshold and a triple threshold in column (5) and column (6), respectively. As illustrated in column (5) from Table 6, the inhibitory influence of innovation efficiency on carbon emissions can be reported at the low level of EMD ($\text{EMD} \le -0.281$, $\beta_1 = -0.475$, $P < 0.01$). After EMD exceeds this critical value, the promoting effect of technical efficiency on carbon emissions is not significant. As displayed in column (5) from Table 6, for the sample with EMD less than the first threshold value or higher than the second threshold value ($\text{EMD} \le 0.092$, $\text{EMD} > 0.122$), increasing innovation efficiency can significantly improve haze pollution. After EMD exceeds the first threshold and lows the second threshold ($0.092 < \text{EMD} \le 0.122$), the inhibitory effect of innovation efficiency is not significant. In summary, innovation efficiency can affect positively carbon and haze co-control under an appropriate level of EMD. Hypothesis 4 is verified.

5 Discussion

ED is designed to achieve an optimal allocation of environmental management authority between various government levels, thereby facilitating various governments to effectively address environmental pollution challenges. Nevertheless, the influence of ED on environmental pollution continues to be controversial. The beneficial effects of ED on environmental pollution have been confirmed by various academics, such as Wu et al., (2020a, 2020b) and Li et al. (2021). Certainly, other academics have also concluded that ED has exacerbated environmental pollution, such as Kunce and Shogren (2007), and Lin and Xu (2022). Additionally, available research on the mechanisms by which ED affects environmental pollution and the allocation of ED continues to be limited. This inspires the motivation for this study. On the base of the dynamic evolution trends in carbon emissions, haze pollution, ED, and innovation efficiency, this study explores the ED threshold effect of innovation efficiency on carbon and haze co-control and the reasonable allocation of ED.

China's provincial carbon emissions and ED performed an increasing trend. This finding is coherent with prior literature. Results from the research of Wang et al. (2020), Sheng et al. (2020), Wu et al. (2021), and Li et al. (2021) indicate since the twenty-first century, China's carbon emissions and ED have continued to grow. Haze pollution and innovation efficiency showed a downward trend. The improvement of haze pollution is closely related to the various pollution reduction policies promulgated by China (Liang et al., 2019; Zhou et al., 2021). Furthermore, the decrease in innovation efficiency can be explained by two primary reasons. One reason is that China is facing a technological blockade from developed countries. Another reason is that China is experiencing limited investment in existing technologies (Curtis, 2016; Shen et al., 2020). Statistics from the Ministry of Commerce of China report that China suffered huge economic losses in 2011 due to the influence of the technology blockade, amounting to more than 32 billion US dollars. At the same time, the share of China's environmental pollution control investment in GDP is declining. For example, China's investment in environmental pollution control was accounting for 1.28% of GDP in 2015 (Qiu et al., 2021; Shen et al., 2020). In addition, provincial carbon emissions, ED, and innovation efficiency show the Matthew effect, and the spatial gap is gradually widening. The central government encourages local governments to give full play to their advantages in management. Local governments have completely different comparative advantages, such as industrial characteristics and energy structure, which are the source of uneven regional development (Wang et al., 2019).

This study analyzes the ED threshold effect of innovation efficiency on carbon and haze co-control by using ED as the threshold variable and innovation efficiency as the mechanism variable. The empirical results support the triple ED threshold of innovation efficiency on carbon and haze reduction co-control. As ED is continuously expanding, the relationship between innovation efficiency and carbon emissions exhibits a W-shape, and its relationship with haze pollution presents an inverted N-shape. Although Li et al., (2019) have provided evidence that industrial structurehas a triple threshold effect on carbon emissions, this study is the first to examine the triple threshold effect of ED on carbon emissions and haze co-control. Findings of the W-shape and inverted N-shape are novel and unexplored. Three primary reasons explain this nonlinear relationship. First, in terms of public goods, the central government endows local governments with certain environmental management responsibilities through ED (Fredriksson & Wollscheid, 2014), which effectively improves the autonomy, flexibility, and efficiency of the allocation of public goods (Alm & Banzhaf, 2012; Garcia-Valiñas, 2007). It is beneficial to the increased scale and structural optimization of investment in innovation resources and the enhancement of innovation efficiency (Feng et al., 2020), thereby achieving the effects of carbon mitigation and haze control. Nevertheless, when ED exceeds a critical threshold, free-riding behavior by local governments is bound to produce an inadequate supply of environmental goods, increasing supply costs and not contributing to innovation efficiency (Gray & Shadbegian, 2004; Grooms, 2015; Helland & Whitford, 2003). Second, in terms of governments, excessive decentralization has resulted in local governments exercising excessive autonomy in environmental management. The promotion championship mechanism drives local governments to compete for performance evaluation, which will lower environmental standards to attract more investment, resulting in a great waste of resources and hindering the positive effect of innovation efficiency on carbon mitigation and haze control (Fredriksson & Millimet, 2002; Kunce & Shogren, 2007). Third, in terms of corporations, unreasonable ED can increase the production cost of corporations, squeeze out innovation investment, and reduce innovation efficiency (Adetutu et al., 2015; Pei et al., 2019). The decline in innovation efficiency is likely to waste resources and deteriorate carbon mitigation and haze control. Consequently, only a reasonable level of ED can effectively curb carbon emissions and haze pollution.

This study further investigates the heterogeneous ED threshold effect of innovation efficiency on carbon and haze co-control. In terms of carbon mitigation, EAD, ESD, and EMD demonstrate the double, triple, and single threshold, respectively. In terms of haze control, EAD, ESD, and EMD, respectively, report the double, triple, and triple threshold, respectively. When the EAD crosses certain thresholds, the positive driving effect of innovation efficiency on carbon emissions and haze pollution is caused by promotion and corruption (Meng et al., 2019; Walter & Luebke, 2013). Promotion tournaments cultivate a phenomenon of GDP worship, in which officials paid more attention to political performance than environmental issues (Smith, 2013; Pu and Fu, 2019). Accordingly, they prefer investment projects with short cycles and quick results, which may have nothing to do with improving innovation efficiency and saving resources (Oyono, 2005). Additionally, corruption can distort resource allocation, reduce innovation efficiency (Ozturk et al., 2019) and worsen environmental problems (Wang et al., 2020). Local governments have better comparative advantages than the central government, including time and economic costs (Zou et al., 2019). They have an accurate understanding of their situation, such as economic development dilemma, public consumption preferences, local environmental protection planning, and environmental governance investment (Goel et al., 2017). Appropriate ESD helps local governments make full use of their comparative advantages to respond to environmental management affairs promptly (Bookovii, 2016; Ran et al., 2020). Environmental monitoring data are the main product of environmental monitoring affairs, which directly reflects the degree of regional environmental pollution and governance. Therefore, if the local government obtains too much monitoring power, local officials are likely to revise and adjust the monitoring data for political performance and promotion (Jia & Nie, 2017). Furthermore, data acquisition requires technical support. Local governments have limited technology and cannot guarantee the quality of monitoring data, which triggers resource misallocation and affects pollution control effects of innovation efficiency (Ran et al., 2020).

In addition, there is a dislocation of negative effects of innovation efficiency on carbon and haze co-control at different levels of heterogeneous ED. This study uses the dislocation in the suppression effect to determine the optimal allocation range of heterogeneous ED. These findings are notable and remarkable. When the logarithmic value of ED is (− 0.270, 0.046), and the influence of innovation efficiency on carbon and haze co-control is negative and significant, which means that innovation efficiency is beneficial to carbon and haze co-control at this level of ED. Similarly, when the logarithmic value of environmental administrative decentralization is (− 0.270, 0.046), the effects of innovation efficiency on carbon and haze co-control perform positively. When the logarithmic value of ESD is (− 0.090, 0.139), innovation efficiency has a negative influence on carbon and haze co-control at this level of ESD. When the logarithmic value of ESD is lower than the first threshold value ($ESD \leq -0.281$), the negative effects of innovation efficiency on carbon and haze co-control are statistically significant. In summary, appropriate ED can achieve carbon and haze reduction, but different types of ED are allocated in different ways. The empirical results suggest that the central government needs not only appropriately expand the administrative and supervision powers of local governments but also reduce the powers of environmental monitoring.

6 Conclusions and implications

How scientifically divide the environmental management authority between the central and local governments is the basic prerequisite and important system guarantee for effectively solving the problem of ecological environmental issues, and it is also a powerful starting point for promoting the green and high-quality development of the economy. This study describes the dynamic evolution trends of China's provincial carbon emissions, haze pollution, ED, and innovation efficiency by kernel density estimation. On this basis, the dynamic threshold model is used to empirically test the ED threshold effect of innovation efficiency on carbon and haze co-control and the reasonable allocation of ED. There are several interesting and novel conclusions. China's carbon emissions and ED are increasing, while haze and innovation efficiency is decreasing. Second, as ED continues to expand, the influence of innovation efficiency on carbon emissions exhibits a W-shape and on haze pollution an inverted N-shape. Third, there are heterogeneous ED threshold effects of innovation efficiency on carbon and haze co-control. Fourth, the carbon and haze co-control effects of innovation efficiency can be strengthened by appropriate ED. The central government requires an appropriate distribution of environmental administration and supervision authority to local governments and a reduction in their environmental monitoring authority.

6.1 Theoretical implications

This study makes a theoretical contribution to current research on ED in three dimensions. The first is an expansion of the research framework on ED. This study theoretically and empirically integrates ED, innovation efficiency, and carbon and haze co-control into the same research framework. This new perspective not only facilitates synergistic control of carbon emissions and haze pollution and reduces policy costs, but also reveals the mechanisms by which ED influences carbon and haze co-control. The second is the mechanisms of heterogeneous ED affecting carbon and haze reduction, this is a focus that cannot be ignored. ED is a complicated system that involves multiple aspects of administration, supervision, and monitoring. Although numerous investigations have attended to the environmental governance effects of heterogeneous ED, theories on the mechanisms by which heterogeneous ED affects carbon and haze co-control are relatively limited. The study addresses these research gaps. The third is how ED achieves optimal allocation. This research question is rarely available in published literature. This study identifies the optimal allocation of ED by highlighting the inhibiting effect of innovation efficiency on carbon and haze reduction under various levels of ED. This enriches their theoretical research on ED.

6.2 Practical implications

This study has practical implications for the optimal allocation of ED. The first is to deal with the allocation of ED authority at various levels of government. The central government should appropriately broaden the environmental authority of local governments to encourage their positive participation in environmental pollution control, enhance regional innovation efficiency, and promote the harmonious development of the regional economy and environment. In the process of ED, various governments should eliminate regional barriers, eradicate local protectionism, strengthen inter-regional coordination in environmental governance, and expand investment in innovation resources, thereby enhancing innovation efficiency. The second is to develop a differentiated ED strategy. The central government should endow local governments with more EAD and ESD, give full advantage to their economic, technological, human resources, and information advantages, and continuously improve the pollution reduction effect of innovative efficiency. EMD in local governments needs to be narrowed. The third is to appropriately increase the level of ED along with strengthening central environmental supervision and inspection. This prevents local governments from being selective in the targets of environmental regulation to maintain continuous economic development.

6.3 Limitations and future research

Several limitations still deserve to be further researched in this study. First, the existing studies have produced various measurement methods of ED, including dummy variables (Grooms, 2015) and indicator methods (Woods & Potoski, 2010). This study simply utilizes the distribution of employees to characterize ED. In future research, a more comprehensive method can be adapted to measure ED and then explore the influence mechanism of ED on carbon and haze co-control. Second, how ED affects carbon and haze co-control is a complicated scientific issue. However, this study tries to use the dislocation in the negative effect of innovation efficiency on carbon and haze co-control at the different levels of heterogeneous ED to determine the optimal allocation range of heterogeneous ED. Other influencing factors have not been considered in the empirical research, such as local government competition (Zhang et al., 2020), government official corruption (Wu et al., 2021), and government environmental preference (Zang & Liu, 2020). In future research, an analysis framework that includes more influencing factors should be established to explore the influence of ED on carbon mitigation and haze control.

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

Declarations

Conflict of interest No potential conflict of interest was reported by the author(s).

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