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RESEARCH ARTICLE

Environmental regulation and green technology innovation: incentive or disincentive effect? New evidence from resource-based cities in China

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Abstract

Under the dual constraints of resources and environment, it is important to stimulate green technology innovation and promote urban development through environmental regulation. Previous literature on the impact of environmental regulation on innovation in green technology has focused only on its unilateral effects, ignoring the bilateral effects of environmental regulation, and has not been fine-tuned for resource-based cities. This study evaluates the disincentive, incentive, and net effects of environmental restrictions on green technology innovation using a bilateral stochastic frontier model for 115 resource-based prefecture-level cities in China from 2010 to 2019. The findings reveal that: (1) Green technology innovation in resource-based cities is subject to both innovation incentives and cost inhibiting effects of environmental regulations. The disincentive effect of environmental regulation in resource-based cities is 28.63%, the incentive effect is 23.83%, and the net effect is −4.8 %. (2) The temporal characteristics of the bilateral effects show that the dominant effects are different in different periods, and the net effect shows a "suppression-promotion" process. In the sample years, the net effect shows a decreasing trend during 2013–2014 and an increasing trend after 2015. (3) For resource-based cities with different life cycles, the impact of environmental regulation on green technology innovation is different, and the average value of the net effect of green technology innovation in resource-based cities is declining, mature, regenerating, and growing cities in descending order.

Keywords Environmental regulation · Green technology innovation · Bilateral stochastic frontier model · Disincentive effect · Incentive effect

Introduction

Resource-based cities are cities where the extraction and processing of minerals, forests, and other natural resources are the main industry in the region, and are divided into four categories: growth, maturity, decline, and regeneration. China now has 262 resource-based cities (Li and Zou 2018), accounting for about 40% of the total number of China's total number of cities. For a long time, the high energy consumption and high emission development methods adopted by various resource-based cities have put the environment and ecology under serious threat. A substantial number of resource-based cities have reached maturity and decline, with some cities even undergoing "mine depletion and city decline." How to deal with the contradiction between resources and the environment in resource-based cities is an urgent issue to be resolved. Green technology innovation can steadily promote economic development based on the rational use of resources using green technology. Therefore, the advancement of green technology is crucial to the growth of resource-based cities.

It is possible to promote green technology innovation over the long term by directing R&D capital investment in that direction (Karakaya et al. 2014), but environmental problems cannot be solved solely through market mechanisms, and environmental regulation is an important means of addressing environmental market failures (Zhao 2013). However, environmental regulation can have both innovation disincentive and incentive effects: the former is that

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environmental regulation causes firms to raise the cost of their products, which in turn may crowd out their green technology development inputs. The latter argues that effective environmental regulation will stimulate firms to innovate in order to improve their competitive path. As a result, it is critical to understand how external environmental regulation affects both innovation incentives and cost increases. When governments impose environmental regulations, how do they affect the progress of regional green technologies? Do environmental regulatory policies affect green technology innovation differently in different cities? How do governments determine which policies are appropriate for which regions?

On this basis, this paper makes the following contributions: (1) there are opposing two-sided effects of environmental regulations, and the net effect under the combined effect can be obtained by decomposing the bilateral effects using bilateral stochastic frontier, which can provide a more comprehensive and three-dimensional understanding of the impact of environmental regulations on green technology innovation. (2) Considering that resource-based cities are facing severe resource and environmental problems, we study for resource-based cities and consider the heterogeneity of green technology innovation in cities with different life cycles.

Literature review

Traditional technical innovation, through improving productivity, producing capacity, and creating economies of scale, is inherently problematic in supporting environmental protection and economic synergy since it increases pollution. In response to major environmental challenges, the government has tightened environmental controls. It is unrealistic to rely just on market mechanisms to address environmental issues, and green technology innovation has emerged as a crucial means of addressing environmental issues through actively investing in green technologies. It is a critical tool for dealing with market failure in the environmental sector. scholars have picked the number of patents, green R&D expenditures, and environmental patent applications as indices of overall innovation or green technology innovation at the national, industry, and business levels (Liu et al. 2022; Tao et al. 2021; Zhang 2015; Fan et al. 2021). They have also investigated the influence of environmental legislation on overall innovation or green technology innovation and reached a variety of results.

In terms of research methodology: scholars confirm the unilateral effects of environmental regulatory policies, either positive or negative, using specific regulatory policies as quasi-natural experiments or spatial Durbin models (Kneller and Manderson 2012; Fan and Sun 2020; Tan and Shang 2018; Zhao et al. 2021; Gao et al. 2022b; Li et al. 2021b; Yang et al. 2021), but sever the combined effects of the two effects on green technology innovation and do not allow quantitative estimation of the combined effects of the two. Deng investigated the dual influence of environmental policy implementation on firms' innovation capacities using a quasi-natural experiment involving energy-saving and low-carbon policy measures and a twofold difference model (Deng et al. 2021). However, in the real situation, local governments' environmental regulations have an impact on green technology innovation, and there is a certain spatial variability in environmental policies, technology innovation, and economic development across regions, which makes it more important to study green technology innovation at the regional spatial level.

From a research perspective, some scholars have conducted studies using panel data of overall prefecture-level cities in China as a sample (Li et al. 2021a; Gao et al. 2021). Gao, for example, explores how heterogeneous environmental regulations affect the impact of FDI on green total factor energy efficiency (Gao et al. 2022a). The relationship between FDI-based environmental regulation intensity and green total factor energy efficiency is verified, but it does not subdivide the sample into resource-based cities, where environmental resource problems are particularly prominent in comparison.

In conclusion, prior research have been unable to provide an united opinion on the unilateral effects of environmental legislation on the invention of green technologies. The key reasons are that the bilateral effects of environmental regulation have not been well investigated and that utilizing models to describe and quantify the bilateral effects has two problems: on the one hand, the estimation methods of traditional models are unable to estimate the exact magnitude of the dual effects; on the other hand, environmental regulation that produces dual effects at. On the other hand, environmental regulation may be affected by both effects in reverse (He and Qu 2015; Deng and Zhang 2020). On the other hand, most existing studies select an overall sample of cities or select resource-based cities within a region for an overall study, without taking into account the heterogeneity of resource-based cities at different development stages. In this paper, we make the following improvements to our previous studies. (1) We address the inevitable endogeneity problem of OLS regressions by using bilateral stochastic frontiers that allow variables to be included in one framework at a time for analysis to investigate the incentives, disincentives, and net effects of environmental regulations in resource-based cities to effectively control for endogeneity due to inter-sample consistency. After that, they are grouped into a complete sample of cases. (2) We focus on a sample of resource-based cities from the overall city sample to analyze the heterogeneity of resource-based cities over different life cycles. (3) In terms of indicator selection, entropy value method is chosen to compensate for the possible shortcomings of single indicator exaggerating the effect of environmental regulation and related variable substitution method; green patent is chosen as a measure of green technology innovation to compensate for the possible subjectivity defects of using keyword collection and the shortcomings of patent grant not reflecting the impact of environmental regulation on performance.

This paper investigates the mechanisms of environmental regulations and how they affect green technology innovation. From 2010 to 2019, we analyze the effects of environmental regulations on green technology innovation in 115 resource-based provincial cities in China. We use bilateral stochastic frontier models to measure disincentives, incentives, and net effects, including the spatial and temporal distribution of these effects and heterogeneity across life-cycle cities.

Mechanism of environmental regulation on green technology innovation

Environmental regulation refers to the restriction and regulation of enterprises' polluting behavior by the government or regulatory agencies in response to the negative externalities of economic activities. In the process of environmental regulation, the government will produce two effects: "compliance cost" and "innovation compensation," i.e., neoclassical economics "inhibition theory" and Porter's hypothesis.

The neoclassical economics "disincentive theory" suggests that enterprises choose to solve the pollution problem by improving their own green technology innovation capacity to achieve green production, which requires a large amount of investment in research and development, while the compliance cost brought by government environmental regulation will squeeze out the funds originally used by enterprises for research and development, and will restrain the management behavior of enterprises. Therefore, environmental regulations may be detrimental to the green technology innovation of enterprises, thus creating a "compliance cost" effect. The cost of compliance effect is mainly manifested in the following three aspects: First, the capital crowding out effect, the implementation of environmental regulations specifies the environmental conditions that enterprises need to meet in order to produce, such as sewage standards, enterprises to meet the development of regulations, it is necessary to improve production and facilities, thereby increasing the investment in production, enterprises often invest in environmental protection than in other areas of investment. The returns obtained are much lower than in other areas. That is, with limited costs, increased investment in environmental protection can squeeze out investment in green technology innovation and research and development. Second, management constraints, environmental regulation will be proposed to make all types of enterprises in product investment decisions and business management activities more subject to environmental constraints, all types of enterprises in making product investment decisions and changes in business management activities, must fully consider the negative impact of these activities on the environment the impact of these activities on the environment will have a binding effect on the behavior of enterprises. The third is the uncertainty of innovation. When the implementation of regulatory policies makes the business environment more uncertain, enterprises will suspend their investment activities and wait for more information to be disclosed before making decisions on whether to invest, resulting in lower R&D investment and lower level of green technology innovation.

The Porter hypothesis suggests that when enterprises choose to increase R&D investment in green technology innovation based on long-term development requirements, and achieve energy-saving and emission-reducing business models and improved production efficiency through technological innovation, the "innovation compensation" effect, which brings additional innovation benefits to enterprises and thus excites them to carry out green technology innovation, will be generated. The "innovation compensation" effect is mainly manifested in the following three aspects: First, environmental regulations increase the emission costs of enterprises, while enterprises must improve their production processes and improve the efficiency of resource allocation through green technology in order to maximize profits, so as to offset or reduce the environmental costs added by the restrictions of government environmental regulation policies. Second, the increase in regulation, public awareness of environmental protection will be enhanced, and companies with green technology have advantages in many aspects, such as easier or government green support, easier to obtain public attention, and companies will take the initiative to develop clean production processes in order to improve market competitiveness. Third, the government green tax-free subsidies, on the one hand, subsidies compensate the cost of following regulations, so that enterprises can invest a lot of money in research and development activities, to stimulate enterprises to carry out green innovation; on the other hand, green subsidies in response to green barriers have an important role, for the failure to meet the environmental and economic standards of developed countries and can not expand foreign markets, green subsidies both to promote environmental energy conservation, but also help enterprises to break through the green subsidies play an important role in addressing green barriers (Fig. 1).

Thus, environmental regulations show inhibiting effects when the "compliance cost" effect dominates and promoting effects when the "innovation compensation" effect dominates."

Model construction and variable selection

Model setting

The bilateral stochastic frontier model proposed by Kumbhakar and Analysis (2008) improves on the traditional stochastic frontier to overcome the defect that the actual output is always smaller than the theoretical output in the traditional stochastic frontier model. The variables in the bilateral stochastic frontier model can be above or below the theoretical frontier value. In recent years, bilateral stochastic frontier models have also been widely used: Lu et al. (2011) study the impact of information asymmetry between doctors and patients in the medical service market on medical prices; Li (2015) studies the assumption of bank risk in the context of interest rate marketization; Tang and Li (2016) study the financing constraints and government subsidies on the investment efficiency of new energy enterprises bilateral and net effects; Shi and Yang (2018) study whether foreign direct investment can have either a spillover or a crowding-out effect on the innovation of firms.

To examine the dual effects of innovation incentives and disincentives of environmental regulation on green technology innovation, and to handle their endogeneity, this study presents a bilateral stochastic frontier model. As both innovation incentives and disincentives of environmental regulation may affect green technology innovation simultaneously, this paper introduces a bilateral stochastic frontier model:

$$gti_{it} = \mu(x_{it}) + \xi_{it}, \xi_{it} = \omega_{it} - u_{it} + v_{it} \quad (1)$$

The gti_{it} is chosen to represent the amount of green patents granted. $\mu(x_{it})$ represents the level of frontier green technology innovation. x_{it} is the vector of characteristics of each city, and control variables that reflect the characteristics of cities and can influence green technology innovation are used in this paper, including industrial structure (ind), level of economic development (eco), government intervention (gov), level of information technology (inf), financial development (fin), and level of human capital (edu). ξ_{it} is a compound disturbance term. ω_{it} represents the upper deviation and indicates the magnitude of the incentive effect. u_{it} represents the lower deviation and indicates the magnitude of the disincentive effect. $\omega_{it} \geq 0$ and $u_{it} \geq 0$ are satisfied. v_{it} is a random disturbance term, and OLS is valid based on the classical assumptions of the econometric model. If the expected mean is not zero, there are "deviations" of the residuals: when $u_{it} = 0$, it indicates the presence of incentive effects only; when $\omega_{it} = 0$, it indicates the presence of disincentive effects only; when $\omega_{it} \neq 0$ and $u_{it} \neq 0$, it indicates the presence of both incentive and disincentive effects.

In (1), $\mu(x_{it}) = x_{it}'\beta$. To measure both the β parameter vector and bilateral effects, the maximum likelihood estimation (MLE) method is used to estimate them. From the previous analysis, it is known that the disturbance terms ω_{it} and u_{it} both have the characteristics of unilateral distribution, so it is assumed that both of them obey exponential distribution, i.e., $u_{it} \sim$ i.i.d.exp (σ_u, σ_u^2), $\omega_{it} \sim i.i.d \exp(\sigma_\omega, \sigma_\omega^2)$. For the disturbance term v_{it}, it is assumed that obeys normal distribution, i.e., $v_{it} \sim$ i.i.d.N $(0, \sigma_v^2)$. v_{it}, u_{it}, and ω_{it} are independent of each other and all of them are independent of the urban characteristic variable. The density function of the composite interferer term ξ_{it} can be calculated as follows:

$$f(\xi_{it}) = \frac{\exp(a_{it})}{\sigma_u + \sigma_\omega}\Phi(\gamma_{it}) + \frac{\exp(b_{it})}{\sigma_u + \sigma_\omega}\int_{-\eta_{it}}^{\infty}\phi(z)dz = \frac{\exp(a_{it})}{\sigma_u + \sigma_\omega}\Phi(\gamma_{it}) + \frac{\exp(b_{it})}{\sigma_u + \sigma_\omega}\phi(\eta_{it}) \quad (2)$$

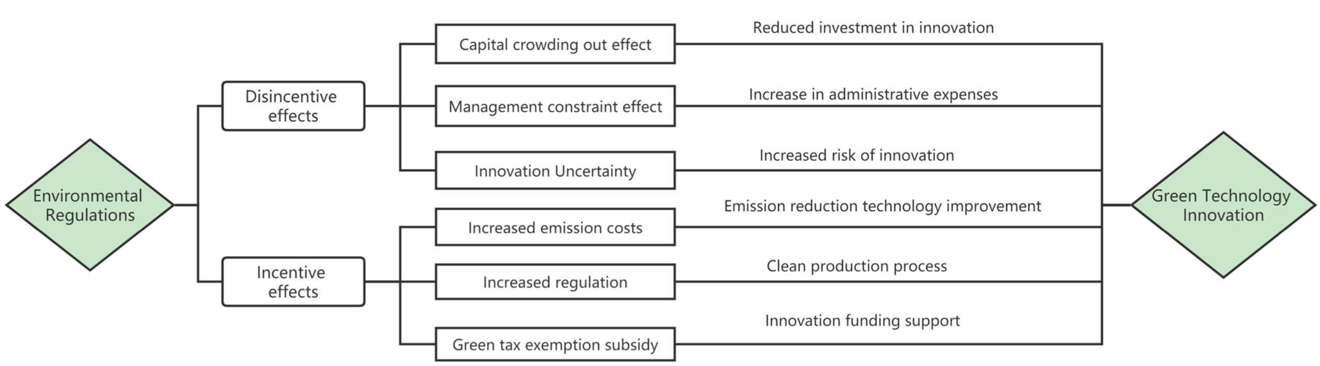


Fig. 1 Bilateral impact of environmental regulation on green technology innovation

where $\Phi(\bullet)$ denotes the standard normal distribution's cumulative distribution function, $\phi(\bullet)$ denotes the standard normal distribution's probability density function, and the remaining parameters are specified as follows:

$$a_{it} = \frac{\sigma_v^2}{2\sigma_u^2} + \frac{\xi_{it}}{\sigma_u}; b_{it} = \frac{\sigma_v^2}{2\sigma_\omega^2} - \frac{\xi_{it}}{\sigma_\omega}; \eta_i = \frac{\xi_{it}}{\sigma_v} - \frac{\sigma_v}{\sigma_\omega}; \gamma_{it} = -\frac{\xi_{it}}{\sigma_v} - \frac{\sigma_v}{\sigma_u} \quad (3)$$

Construct the log-likelihood function as follows to acquire the above parameter estimations for the collection of n observations:

$$\ln L(X;\theta) = -n \ln(\sigma_u + \sigma_\omega) + \sum_{i=1}^{n} \ln\left[e^{a_{it}}\Phi(\gamma_{it}) + e^{b_{it}}\Phi(\eta_{it})\right] \quad (4)$$

In (4), $\theta = [\beta, \sigma_v, \sigma_\omega, \sigma_u]'$. This paper focuses on the disincentive and incentive effects, so we further derive the conditional density functions of u_{it} and ω_{it} denoted as $f(u_{it} \mid \xi_{it})$ and $f(\omega_{it} \mid \xi_{it})$ respectively as follows:

$$f(u_{it} \mid \xi_{it}) = \frac{\lambda \exp(-\lambda u_{it})\,\Phi(u_{it}/\sigma_v + \eta_{it})}{\Phi(\eta_{it}) + \exp(a_{it} - b_{it})\,\Phi(\gamma_{it})} \quad (5)$$

$$f(\omega_{it} \mid \xi_{it}) = \frac{\lambda \exp(-\lambda\omega_{it})\,\Phi(\omega_{it}/\sigma_v + \gamma_{it})}{\exp(b_{it} - a_{it})\left[\Phi(\eta_{it}) + \exp(a_{it} - b_{it})\,\Phi(\gamma_{it})\right]} \quad (6)$$

In (5) and (6), $\lambda = \frac{1}{\sigma_u} + \frac{1}{\sigma_\omega}$. Based on the above mentioned conditional distribution, the conditional expectations of u_{it} and ω_{it} are obtained as follows:

$$E\left(1 - e^{-u_{it}} \mid \xi_{it}\right) = 1 - \frac{\lambda}{1+\lambda}\frac{\left[\Phi(\eta_{it}) + \exp(a_{it} - b_{it})\exp\left(\sigma_v^2/2 - \sigma_v\gamma_{it}\right)\Phi(\gamma_{it} - \sigma_v)\right]}{\Phi(\eta_{it}) + \exp(a_{it} - b_{it})\,\Phi(\gamma_{it})} \quad (7)$$

$$E\left(1 - e^{-\omega_{it}} \mid \xi_{it}\right) = 1 - \frac{\lambda}{1+\lambda}\frac{\left[\Phi(\gamma_{it}) + \exp(b_{it} - a_{it})\exp(\sigma_v/2 - \sigma_v\eta_{it})\,\Phi(\eta_{it} - \sigma_v)\right]}{\exp(b_{it} - a_{it})\left[\Phi(\eta_{it}) + \exp(a_{it} - b_{it})\,\Phi(\gamma_{it})\right]} \quad (8)$$

With the above equation, the net effect can be obtained by comparing the incentive effect with the disincentive effect.

$$NS = E\left(1 - e^{-\omega_{it}} \mid \tilde{\zeta}_{it}\right) - E\left(1 - e^{-u_{it}} \mid \tilde{\xi}_{it}\right) = E\left(e^{-u_{it}} - e^{-\omega_{it}} \mid \tilde{\zeta}_{it}\right)' \quad (9)$$

Since the parameter σ_u appears only in a_{it} and γ_{it}, while σ_ω appears only in b_{it} and η_{it}, both 141 are identifiable. Therefore, there is no need to assume the relative magnitude of the two effects in the follow-up test, and the effect size is entirely determined by the measurement results, which is more objective compared to the traditional regression analysis method.

Data sources

There are 262 resource-based cities in China, including 126 prefecture-level administrative regions (including prefecture-level cities, regions, autonomous prefectures, leagues), 62 county-level cities, 58 counties (including autonomous counties, forest areas), and 16 municipal districts (development zones, management zones). In this paper, 126 prefecture-level administrative regions are selected as research samples; firstly, to ensure data availability and comparability, all prefecture-level cities are selected; secondly, for the purpose of type analysis, the samples are selected to include growth, mature, declining, and regenerative resource-based cities. However, due to the serious lack of data in some cities, the sample was finally determined to be 115 prefecture-level administrative regions in order to ensure the completeness and availability of data. The planning period of China's National Resource-based City Development Plan 2013–2020 is 2013–2020, and to incorporate the changes in the sample before as well as after the plan, this paper selects the sample period as 2010–2019, with a total of 1150 observations. The indicator data were obtained from the China Environment Yearbook, the China Urban Statistical Yearbook, and the China Urban Database. For the missing data of resource-based cities in individual years, they were complemented by linear interpolation.

Variable selection

Explanatory variable: green technological innovation (gti)

This paper adopts the number of green invention patent applications as its evaluation index, matched according to the green list of WIPO's international patent classification. The reasons for this mainly include the following two points: firstly, the declaration of green invention patents has a higher technological threshold, which better reflects high-level green innovation (Amore and Bennedsen 2016). Second, compared with the number of patents granted, the patented technology may have an impact on the development of enterprises during the application process, and the number of patent applications can be selected for a more effective (Qi et al. 2018) and comprehensive measurement.

Core explanatory variable: environmental regulation (er)

In choosing the specific measurement method and indicator system of environmental regulation, the specific characteristics and requirements of urban environmental regulation implementation should be fully considered first. In this paper, drawing on the practice of Fu and Lisa (2010), in order to solve the one-sidedness arising from the evaluation with a single index or a single alternative variable (Li and Zou 2018), the entropy value method is used to construct the environmental regulation intensity of 115 cities in China based on the actual pollution indicators of each industry, and the indicators used are listed in Table 1 below,The higher the value of environmental regulation, the higher the intensity of environmental regulation in that city.

The measurement method is manifested by first standardizing the data. For positive indicators:

$$X'_{ij} = \left(X_{ij} - \min\{X_i\}\right) / \max\{X_i\} - \min\{X_i\}\Big) \tag{10}$$

For negative indicators:

$$X'_{ii} = (\max\{X_i\} - X_{ii}) / \max\{X_i\} - \min\{X_i\}\big) \tag{11}$$

Calculate the weight of the index value:

$$Y_{ij} = X'_{ij} / \sum_{i=1}^{m} X'_{ij} \tag{12}$$

Calculate index information entropy:

$$e_j = -k \sum_{i=1}^{m} \left(Y_{ij} \times \ln Y_{ij}\right) \tag{13}$$

In (13), $k = \frac{1}{\ln m}$, $0 \le e_j \le 1$, and calculate the redundancy of information entropy:

$$d_j = 1 - e_j \tag{14}$$

Indicator weights:

$$w_i = d_i / \sum_{j=1}^{n} d_j \tag{15}$$

Overall Score:

$$S_i = \sum_{j}^{n} w_i X'_{ij} \tag{16}$$

Control variables

Besides being affected by environmental regulations, green technology innovation is also influenced by industrial structure, economic development level, and government intervention, etc. Based on the actual situation of this paper and previous research results, and drawing on existing practices (Wu et al. 2021), the following control variables are selected.

(1) Industrial structure (ind). As industrial structure changes, it affects production efficiency, human resources, and capital allocation, along with the development of green technology. We utilize the rise in tertiary industry as a share of GDP for each prefecture-level city in this article (Liu and Yuan 2018; Fan and Sun 2020).

(2) The level of economic development (eco). Green technology innovation necessitates a significant amount of cash and expertise, and the more developed the economy, the more it may encourage the use of diverse production variables for green technology innovation. The GDP per capita of each prefecture-level city is used to express in this article.

(3) Government intervention (gov). Due to the potential for technological spillover in green technology innovation, enterprises are responsible for all of the costs, but they cannot monopolize the results. This identifies a market failure, and direct government intervention averts it. In this study, we express the percentage of general budget spending to regional GDP (Liu and Yuan 2018; Fan and Sun 2020; Liu et al. 2017).

(4) Information level (inf). The construction of information infrastructure can achieve an efficient level of informatization and influence technology diffusion and innovation. In this paper, we use the number of Internet users in each municipality to express it.

(5) Financial development (fin). Financial development provides financial assurance for green technology innovation. The year-end loan balance of financial institutions in each prefecture-level city is used to represent it in this study.

(6) Human capital level (edu). Technical innovation is carried by people, and expanding green technology innovation capacity requires human capital to be engaged in innovation support services. This paper uses the ratio of the number of general undergraduate and above population to the number of resident population in the city to measure human capital (He et al. 2020).

Table 1 Environmental regulation entropy method variables

Category	Variables
Positive indicators	General industrial solid waste comprehensive utilization rate (sol)
	Harmless disposal rate of domestic waste (gar)
Negative indicators	Industrial sulfur dioxide emissions (so2)
	Industrial smoke emissions (smo)
	Industrial wastewater emissions (wa)

The variables are treated as logarithms to remove the influence of heteroskedasticity on data smoothness, but negative values or a small number of zero values would be generated as a result, and the relative magnitudes between data did not change, and a small amount of data was not processed manually to ensure data integrity and objectivity. Table 2 displays statistical descriptions of the pertinent variables.

Empirical results and analysis

Model setting and influencing factors of green technology innovation

This part of the model estimation is divided into two steps: Using the bilateral stochastic frontier model developed in Chapter 3, first, the effects of city characteristics, such as economic development and government intervention, on green technology innovation are estimated, then the two-way effects of environmental regulation on green technology innovation are estimated. The estimation results are shown in Table 3.

As shown in Table 3: model m1 is the result of OLS estimation, models m2 to m5 are all estimated using MLE under bilateral stochastic frontier, and model m2 is the result under constraints $\ln\sigma_u = \ln\sigma_\omega = 0$. Models m3 and m4 include environmental regulation to identify the suppression effect and incentive effect, respectively, and model m5 includes both effects of environmental regulation. Based on the results of our statistical analysis, OLS regression methods indicate that government intervention level negatively affects the level of green technologies innovation, whereas economic development, information technology, finance, industrial structure, and human capital positively affect the level of green technologies innovation. Among them, the level of information technology and financial development are one of the main factors that cause green technology innovation. The higher the level of information technology of enterprises, the more efficient technology platform provided can lay the foundation for the development of green technologies and products of enterprises. Due to the innovation spillover effect existing in information technology itself can prompt enterprises to obtain technical knowledge with higher efficiency or lower cost, which can more easily promote the development of green technology innovation. The higher the level of financial development is, the more it is able to bring large-scale financing to innovative subjects, thus providing long-term incentives and risk diversification functions for green technology innovators and promoting the long-term effectiveness of green technology innovation. The above results are similar to those estimated in the existing literature, indicating that the use of bilateral stochastic frontier estimation does not lead to large bias in the results. The robustness of the model is shown in the fact that the regression results of model m2 and model m5 of the bilateral stochastic frontier model are quite close to one another. The effect of model fitting steadily increases with the addition of environmental control variables, and model m5 outperforms other models. The subsequent variance decomposition and accompanying statistical analysis are mostly based on model m5, as well. From model m5, we can see that both the disincentive and incentive effects of environmental regulation are significant. Taking these results into account, we can conclude that the positive and negative effects of environmental regulations in the area of green technology innovation are present simultaneously. It is possible for the model design to be biased if the one-sided estimating approach is utilized; that is, if only the incentive effect or only the disincentive impact is taken into consideration.

Variance decomposition

The results of the analysis are presented in Table 4, where the bilateral effect of environmental regulation accounts for 53.32% of the total utility, indicating that 53.32% of the total variance is determined by disincentives and incentives. $E(\omega - u) = -0.087$. This indicates that the disincentives are

Table 2 Descriptive statistics

Variables	VarName	Obs	Mean	SD	Median	Min	Max
Green technology innovation	lgti	1150	4.33	1.33	4.369	0.000	8.239
Environmental regulation	ler	1150	−0.42	0.14	−0.386	−1.514	−0.041
Level of economic development	leco	1150	10.53	0.57	10.493	8.773	12.456
Informationization level	linf	1150	12.90	0.80	12.924	9.210	15.151
Financial development	lfin	1150	15.85	0.77	15.844	13.585	18.315
Industrial structure	lind	1150	3.60	0.24	3.618	2.278	4.121
Government intervention	lgov	1150	2.98	0.45	2.950	1.479	4.394
Government intervention	ledu	1150	−0.29	0.88	−0.215	−4.017	1.780

Table 3 Bilateral stochastic frontier estimation results

	m1	m2	m3	m4	m5
leco	0.340***	0.295***	0.322***	0.290***	0.274***
	(6.460)	(3.231)	(6.069)	(5.283)	(4.958)
linf	0.610***		0.582***	0.594***	0.577***
	(13.371)		(11.131)	(11.217)	(10.963)
lfin	0.654***	1.164***	0.722***	0.704***	0.742***
	(12.571)	(19.870)	(12.234)	(11.809)	(12.333)
lind	0.255**	0.497**	0.163	0.150	0.132
	(2.239)	(2.455)	(1.447)	(1.303)	(1.155)
lgov	−0.413***	−0.576***	−0.475***	−0.526***	−0.553***
	(−5.797)	(−3.997)	(−6.585)	(−6.933)	(−7.241)
ledu	−0.008	−0.029	−0.023	−0.019	−0.022
	(−0.325)	(−0.729)	(−0.988)	(−0.816)	(−0.957)
_cons	−17.171***	−17.252***	−17.110***	−16.429***	−16.512***
	(−23.103)	(−12.791)	(−23.682)	(−21.962)	(−22.079)
sigma_v					
_cons		−4.009	−0.728***	−0.713***	−0.736***
		(−0.838)	(−7.553)	(−7.359)	(−7.518)
sigma_u					
ler			−1.248***		−0.917***
			(−3.797)		(−2.792)
_cons		0.000	−1.449***	−0.903***	−1.305***
		(.)	(−7.141)	(−8.626)	(−6.800)
sigma_w					
ler				2.473***	1.856**
				(2.818)	(2.379)
_cons		0.000	−1.137***	−0.194	−0.397
		(.)	(−7.538)	(−0.700)	(−1.466)
N	1150	1150	1150	1150	1150
Log likelihood		−1478.489	−1220.395	−1219.753	−1215.713
r2_a	0.715				
LR(chi2)			516.188	517.472	525.552
p-value			0.000	0.000	0.000

***, **, and * denote significance at the 0.01, 0.05, and 0.1 levels, respectively

dominant, thus indicating that the level of green technology innovation in resource-based cities is lower than the optimal level, i.e., the neoclassical economics "disincentive theory" is verified in this sample. In terms of the ratio of the inhibitory and incentive effects of environmental regulation, the inhibitory effect is 61.91% and the incentive effect is 38.09%, which explains the total variance. This indicates that the level of green technology innovation in China basically depends on environmental regulation, and the inhibitory effect dominates the combined effect.

Further analyzing the specific magnitudes of the bilateral and net effects of environmental regulations that deviate green technological innovation from the optimal level, the magnitudes of the inhibitory and incentive effects are calculated by Eqs. 7 and 8, respectively, and the estimated results are presented in Table 5, which yield the inhibitory effect of environmental regulations in resource-based cities as 28.63%, the incentive effect as 23.83%, and the net effect as −4.8%. This indicates that the inhibitory effect of environmental regulation makes the level of green technology innovation lower than the optimal level of 28.63%, the incentive effect of environmental regulation makes the level of green technology innovation lower than the optimal level of 23.83%, and the combined effect of the two offsetting effects makes the level of green technology innovation lower than the optimal level of 4.8%. This indicates that due to the simultaneous existence of bilateral effects and the different magnitudes of the

Table 4 Incentive and disincentive effects of environmental regulation

	Variable meaning	Symbol	Measurement coefficient
Bilateral effects	Random error term	σ_v	0.4792
	Cost disincentive effect of environmental regulation	σ_u	0.4030
	Innovation incentive effect of environmental regulation	σ_ω	0.3161
Variance decomposition	Total variance of the random term	$\sigma_v^2 + \sigma_u^2 + \sigma_\omega^2$	0.4919
	Weight of bilateral effects	$\frac{\sigma_u^2+\sigma_\omega^2}{\sigma_v^2+\sigma_u^2+\sigma_\omega^2}$	53.32%
	Weight of disincentive effect	$\frac{\sigma_u^2}{\sigma_u^2+\sigma_\omega^2}$	61.91%
	Weight of incentive effect	$\frac{\sigma_\omega{}^2}{\sigma_u^2+\sigma_\omega{}^2}$	38.09%

effects, environmental regulations show inhibitory effects on green technology innovation. Overall environmental regulation incentivizes firms to develop technology and grow revenues to balance the cost of environmental regulation, resulting in a level of green technology innovation that is 23.83% above the optimal level in resource-based cities. Environmental regulation makes resource-based cities face many constraints not only to strengthen their manufacturing facilities and diversify their inputs. The environmental pollution initially borne by the public internalizes the external environmental costs, and the increase in costs will directly lead to a reduction in output and weaken market competitiveness, making the level of green technology innovation 28.63% below the optimal level. Regulatory regulations have a negative cost inhibiting effect, but environmental regulations also have a positive incentive effect which somewhat mitigates this negative effect. This cost-inhibiting effect cannot be removed completely, and green technology innovation in resource-based cities in China is not very high.

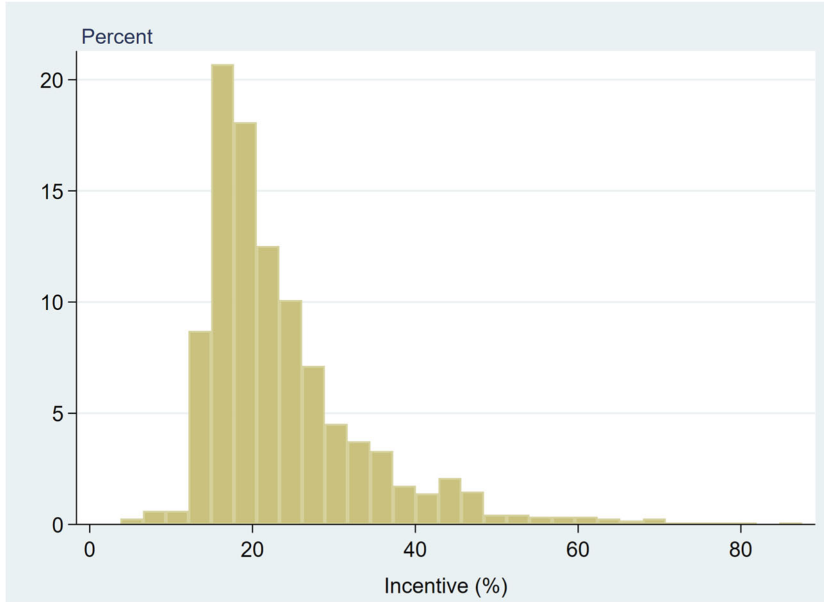
Table 5 shows the incentives and disincentive effects of environmental restrictions on green technology innovation at the first quartile, second quartile, and third quartile of the distribution, respectively. Furthermore, the net effect at the 75th percentile is positive 7.54, suggesting that the positive effect from environmental regulation can be found in more than a quarter of resource-based cities. Accordingly, the innovation of green technologies in resource-based cities is 7.54% higher than the frontier level.There has been a reduction in green technology innovation compared to the frontier level at the 25th and 50th percentiles. In cities with a heavy reliance on natural resources, environmental regulations have a stronger disincentive effect than an incentive effect. This results in a negative net effect on green technology innovation. In many resource-based cities, environmental regulations actually inhibit the development of green technologies. This means that environmental regulations negatively affect the level of green technology innovation in these communities. However, there are some resource-based cities that are able to reduce the negative impact of regulation or even positively promote green technology innovation.

Figures 2, 3, and 4 summarize the frequency distribution of disincentive, incentives for innovation, and the net impact of environmental regulations on the development of green technologies in a more direct manner. Regardless of whether environmental regulation inhibits or encourages green technology innovation, as shown in Figs. 2 and 3, a noticeable trend can be observed to the right, as shown in Fig. 2. The trailing effect is caused by a direct cost disincentive effect caused by environmental regulation. It can be seen that green technology innovation is still trailing in 80% of the locations, while innovation incentive effects mostly disappear at 60% of the locations. It is noted in Fig. 4 that about one-third of the resource-based cities receive positive incentives for green innovation activities, while the net effect of the remaining cities is less than zero, i.e., the degree of technology innovation is much lower than the frontier level, which also shows that most resource-based cities have stricter rules that make it harder for green innovation to happen.

Table 5 Estimation of bilateral effects

	Mean	SD	p25	p50	p75
Environmental regulation incentive effect	23.83	10.46	16.96	20.64	27.41
Environmental regulation disincentive effect	28.63	13.07	19.74	24.55	33.17
Net effect	−4.8	21.19	−16.44	−3.95	7.54

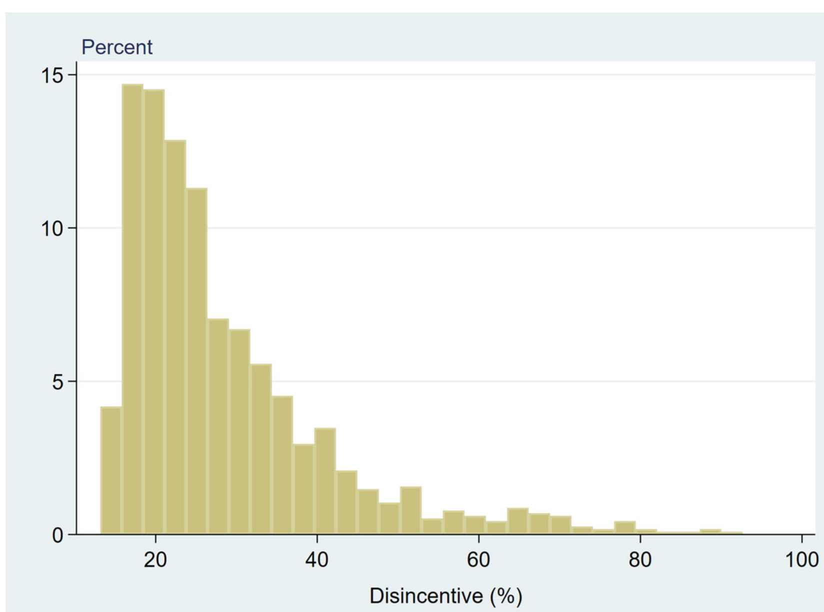
Fig. 2 Incentive



Temporal characteristics of environmental regulation affecting green technology innovation

Table 6 shows the statistical analysis of environmental regulations on green technology innovation by year. Within the sample years, the incentive effect shows an overall upward trend and the inhibitory effect shows an overall downward trend, with fluctuations in the opposite direction during 2013–2014. Although there are two opposing effects of environmental regulation, the dominant effect differs from period to period. From a static perspective, before the implementation of the regulation policy, enterprises themselves used effective resource allocation to maximize their profits, while the emergence of regulation made enterprises increase the "compliance cost" to meet the policy requirements; in the long run, the regulation policy was continuously improved to induce enterprises to green innovation more clearly. From a dynamic point of view, enterprises will be less competitive at the beginning of the regulation because of the temporary increase in costs, but as time develops, enterprises find that the "cost of compliance" is high and unsatisfactory, and they will actively seek to improve their production methods and carry out green technology innovation to enhance their competitiveness in the market. Starting from the sample period chosen in this paper: on the one hand, 2011 was

Fig. 3 Disincentive



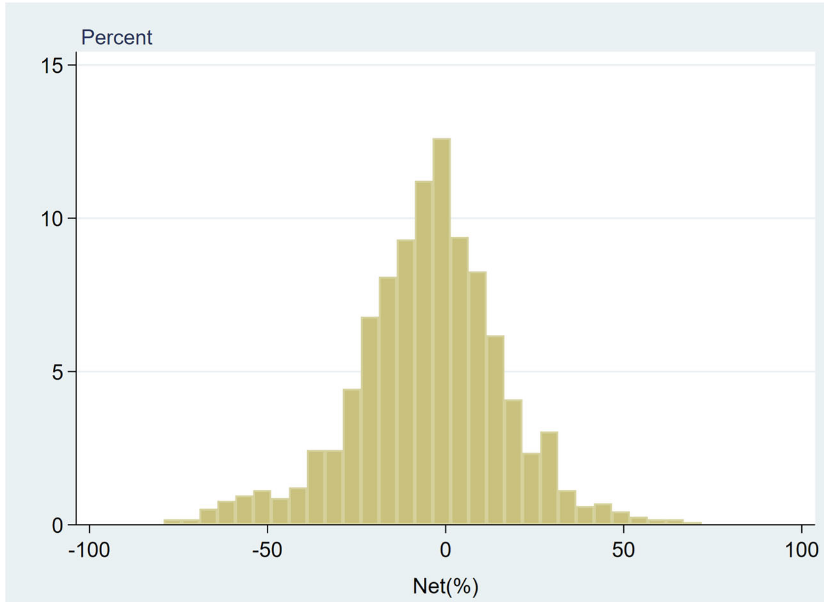


Fig. 4 Net

the beginning of China's 12th Five-Year Plan, and the 12th Five-Year Comprehensive Work Plan for Energy Conservation and Emission Reduction was issued, which will have an impact on the development of resource-based cities; on the other hand, the National Sustainable Development Plan for Resource-based Cities The National Sustainable Development Plan for Resource-based Cities was released in 2013. The implementation of such regulatory policies has a tendency to inhibit and then promote the effect of resource-based green technology innovation, which is exactly in line with the findings of some scholars. The nonlinear effect of environmental regulation on urban sustainable development efficiency (He and Hu 2022). Overall, the net effect of environmental regulation shows an overall slow upward trend.

Taking into account the quantile perspective, the disincentive effect of environmental regulation stands out in the first quantile and demonstrates a significant downward trend; the net effect shifts from negative to positive over time in the second quantile and demonstrates an upward trend; and in the third quantile, the positive incentive effect stands out and demonstrates an overall upward trend. In general, this indicates that environmental regulation is reducing the disincentive effect on innovation, and that the predicted results over time are consistent with the previous predictions, thus proving that the findings presented in this paper are reliable (Figs. 5, 6, 7, and 8).

Regional characteristics of environmental regulation affecting green technology innovation

The mean values of the net effect of green technology innovation in resource-based cities are, in descending order, declining, mature, regenerative, and growing. Figure 9 shows that more than half of the declining cities have a positive net effect of environmental regulation, and the green innovation incentive of environmental regulation is significant. It indicates that these cities are nearing resource depletion and the share of resource industries is decreasing, and for facing the urgent problem of transforming the economic development mode, it is difficult to achieve self-transformation without external help. However, in recent years, with the support of policies such as the "Planning" for the layout of major national industrial projects, which explicitly proposes "one city, one policy" for such cities to develop alternative industry cultivation programs, and the National Development and Reform Commission's cumulative arrangement of central budget investment of about 17 billion yuan to support resource-depleted cities, the industrial structure has been continuously optimized and upgraded. Promote the level of green technology innovation in cities (Sun et al. 2020). Figure 10 shows that environmental regulation makes the level of green technology innovation in a small number of mature cities higher than the frontier level, and the net effect of individual mature cities is much higher than that of the other three types of cities. However, there are still a larger proportion of cities where the innovation incentive effect cannot compensate for the cost inhibiting effect, and the net effect is negative. This category has many years of mining experience and mature transportation and processing systems, but their backward production capacity and the accumulation of long-term social as well as environmental problems have brought them into the dilemma of stagnant green technology innovation development. Figure 11 shows that most of the growing

Table 6 Annual distribution of bilateral effects of environmental regulation

year	Impact effect	Mean	SD	p25	p50	p75
2010	Incentive effect	20.59	7.73	15.36	18.37	24.14
	Disincentive effect	31.97	14.68	20.92	27.74	37.99
	Net effect	−11.38	20.55	−22.5	−9.12	3.04
2011	Incentive effect	21.07	7.78	15.73	19.36	24.2
	Disincentive effect	30.88	15.27	19.72	26.23	37.52
	Net effect	−9.81	21.32	−20.2	−6.95	4.53
2012	Incentive effect	22.26	10.24	15.61	19.49	25.11
	Disincentive effect	29.7	14.21	20.63	24.78	35.64
	Net effect	−7.44	21.82	−20.55	−4.62	3.89
2013	Incentive effect	21.21	9.35	15.81	18.28	22.93
	Disincentive effect	32.2	14.93	21.81	28.84	39.38
	Net effect	−10.99	21.94	−22.31	−10.18	1.13
2014	Incentive effect	21.32	8.81	15.7	18.26	24.24
	Disincentive effect	32.59	15.84	21.1	27.92	37.94
	Net effect	−11.27	22.41	−21.66	−10.7	3.13
2015	Incentive effect	24.3	12.27	16.52	20.3	27.31
	Disincentive effect	28.4	12.49	19.78	24.97	32.8
	Net effect	−4.1	22.11	−15.7	−4.87	8.32
2016	Incentive effect	26.03	12.45	17.66	21.58	29.87
	Disincentive effect	27.11	11.26	19.18	23.87	32.82
	Net effect	−1.09	21.34	−14.74	−1.56	10.69
2017	Incentive effect	27.41	11.69	18.99	23.6	31.76
	Disincentive effect	24.87	8.91	18.53	22.36	29.45
	Net effect	2.54	18.83	−10.26	0.65	13.11
2018	Incentive effect	27.52	11.49	19.33	24.82	30.89
	Disincentive effect	24.59	8.3	18.99	22.13	28.37
	Net effect	2.93	18.12	−8.87	2.75	11.66
2019	Incentive effect	26.64	7.99	20.83	24.79	29.79
	Disincentive effect	24.03	8.03	18.93	21.87	26.69
	Net effect	2.61	14.82	−5.86	3.02	11.58
Total	Incentive effect	23.83	10.46	16.96	20.64	27.41
	Disincentive effect	28.63	13.07	19.74	24.55	33.17
	Net effect	−4.8	21.19	−16.44	−3.95	7.54

cities still have negative green technology innovation efficiency, indicating that the innovation incentive effect brought by environmental regulations in this part of the city has not yet been highlighted and is in the early stage of resource development and utilization. These cities have large reserves of various resources and can be exploited for a long period of time; the low returns of green technology innovation in the short term cannot attract such enterprises to shift from expanding resource development to green technology innovation. Figure 12 shows that environmental regulations make the level of green technology innovation in most regenerative cities lower than the frontier level; these cities have stopped most of the resource exploitation, and the development of green technology industry still lags behind due to the low correlation between traditional industries and green industries, which are also not suitable to be transformed into green industries.

Robustness test

In addition, this paper conducts a robustness test by replacing the explanatory variables and choosing the

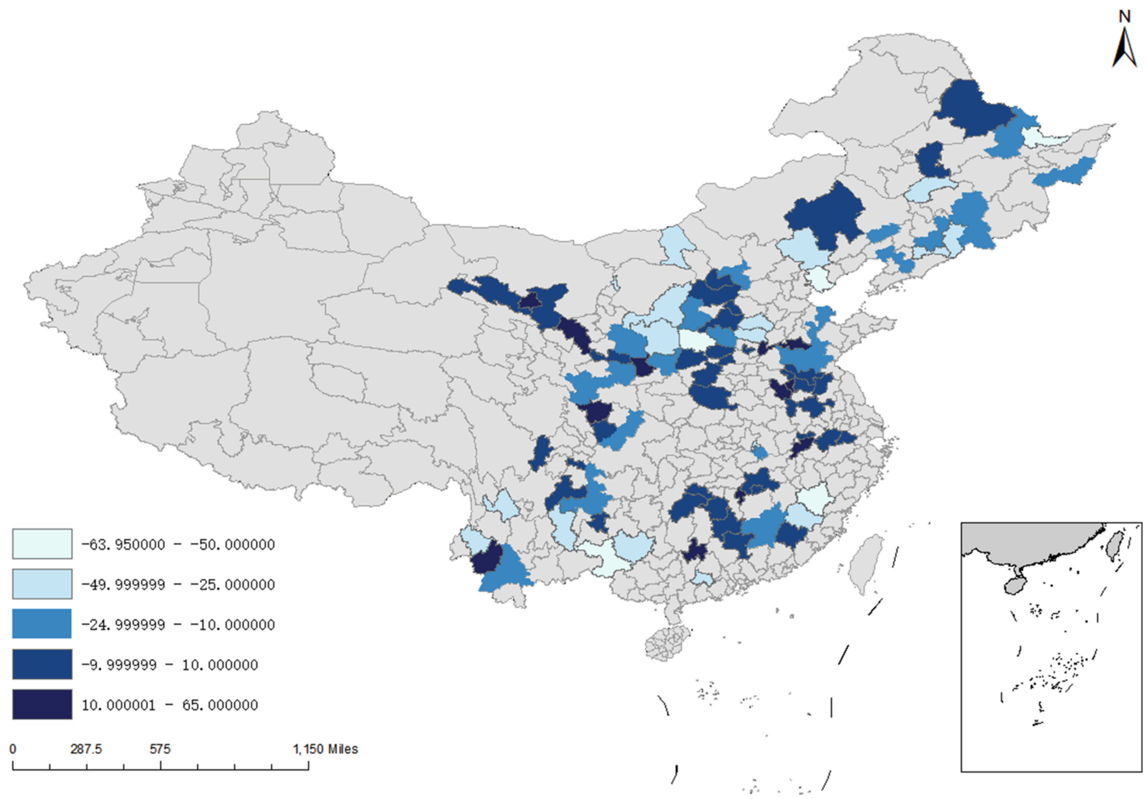


Fig. 5 Net effect in 2010

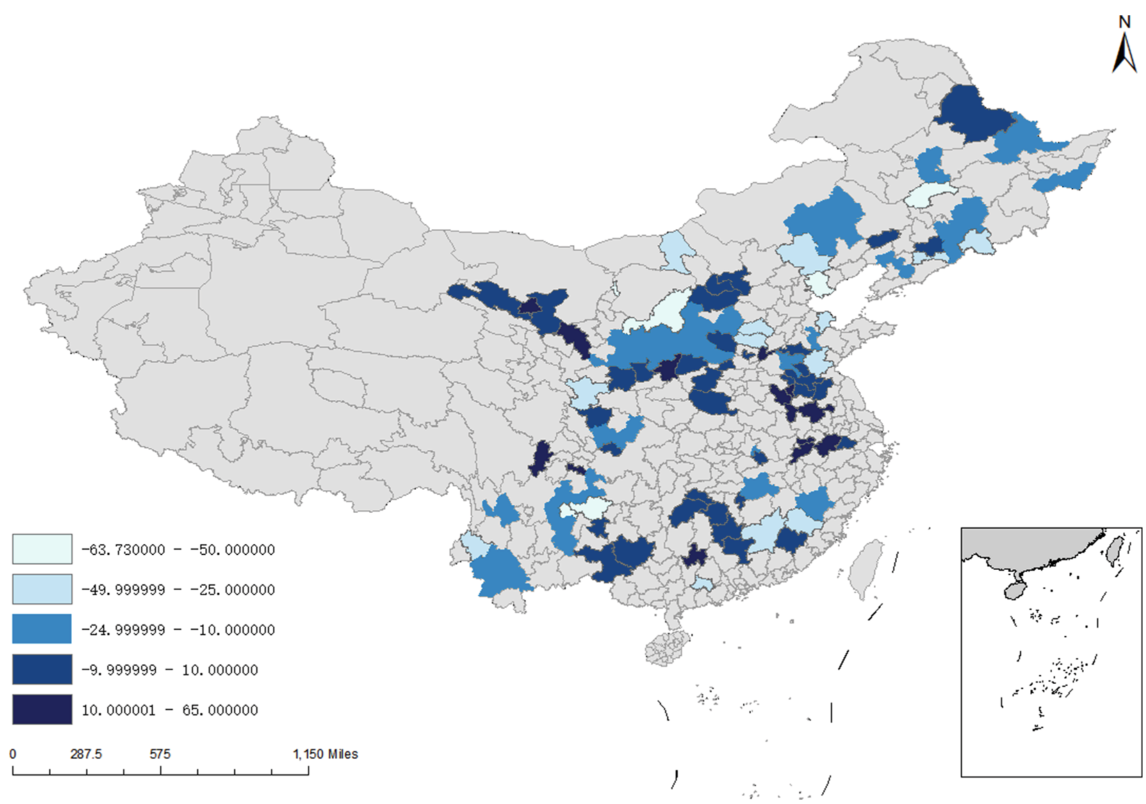


Fig. 6 Net effect in 2013

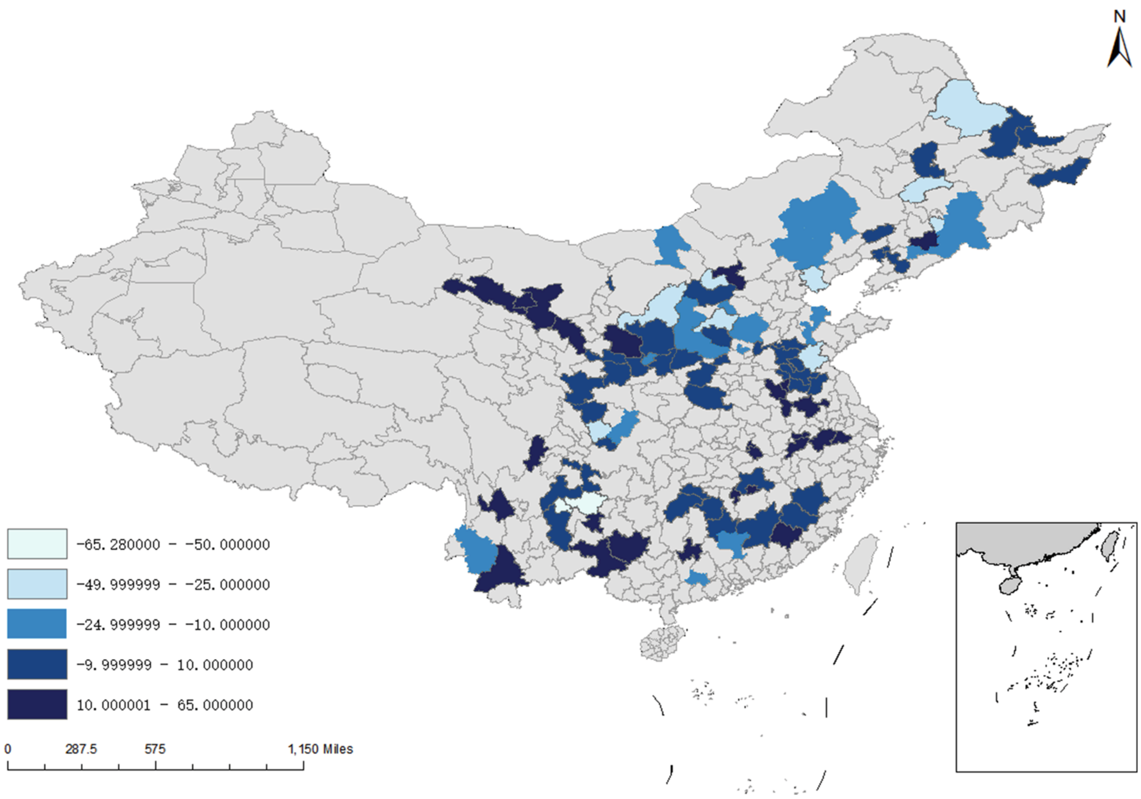


Fig. 7 Net effect in 2016

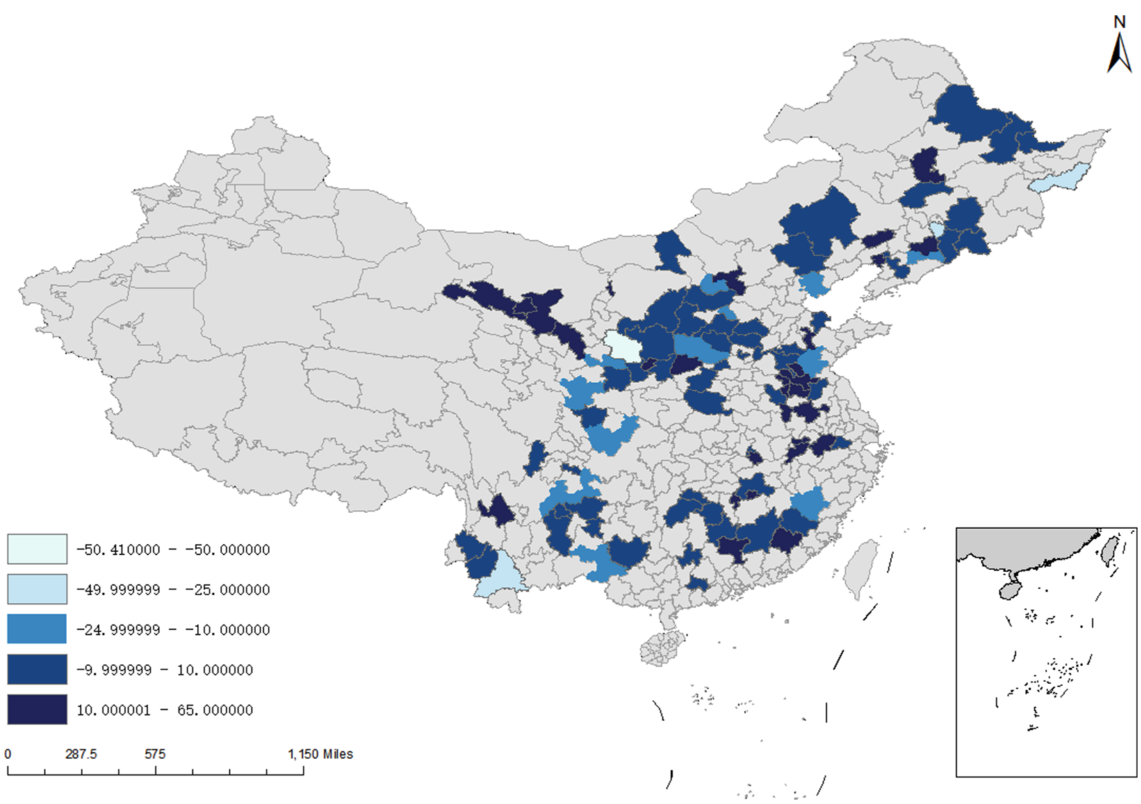
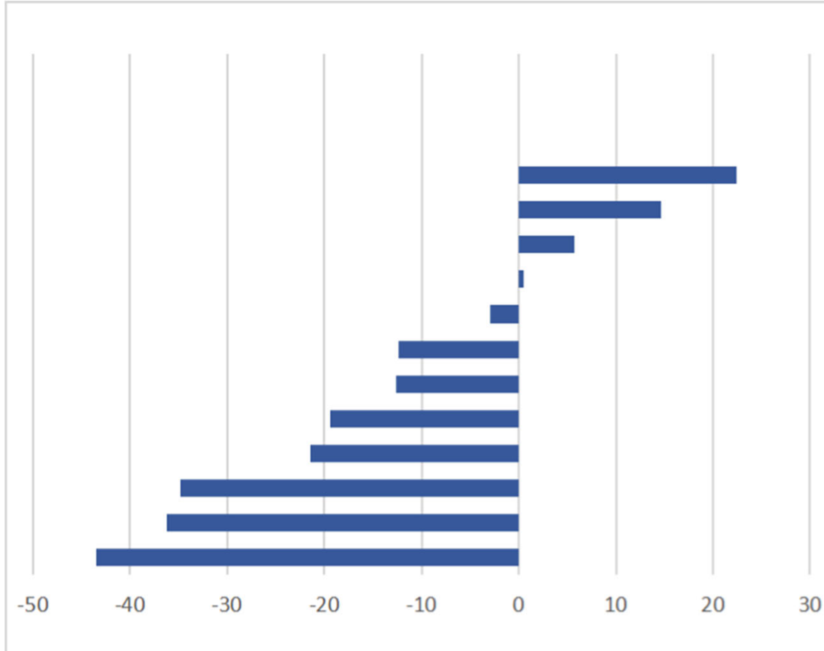


Fig. 8 Net effect in 2019

Fig. 9 Growing cities



number of green utility model patents filed to measure green technology innovation to determine how reliable the findings presented in this work really are. Due to the limited space of the article, the corresponding regression results are not presented, and only the results of the variance decomposition of the corresponding inhibitory and incentive effects, as well as the distribution of the effects, are presented.

The results of the analysis are presented in Table 7, where the bilateral effect of environmental regulation accounts for 53.32% of the total utility, indicating that 60.74% of the total variance is determined by disincentives and

Fig. 10 Mature cities

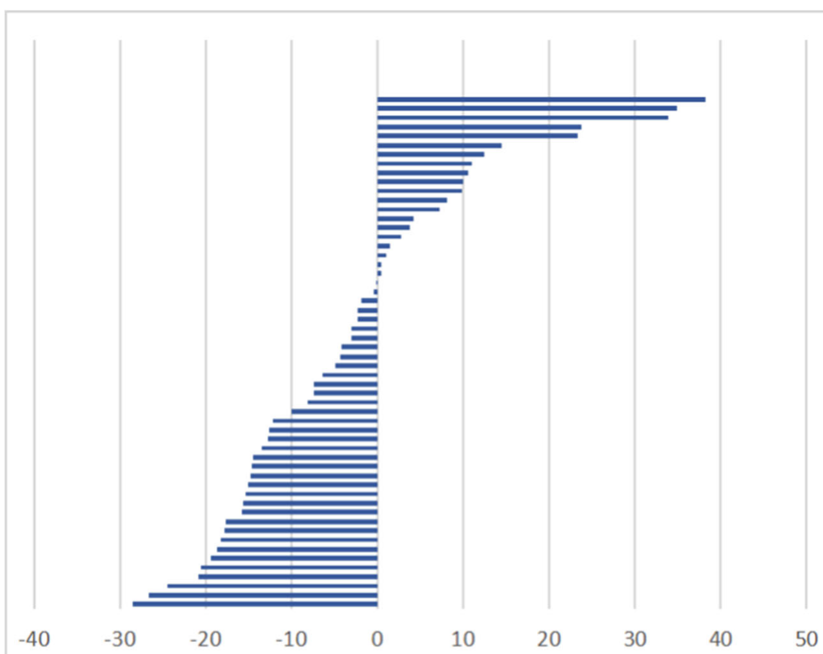
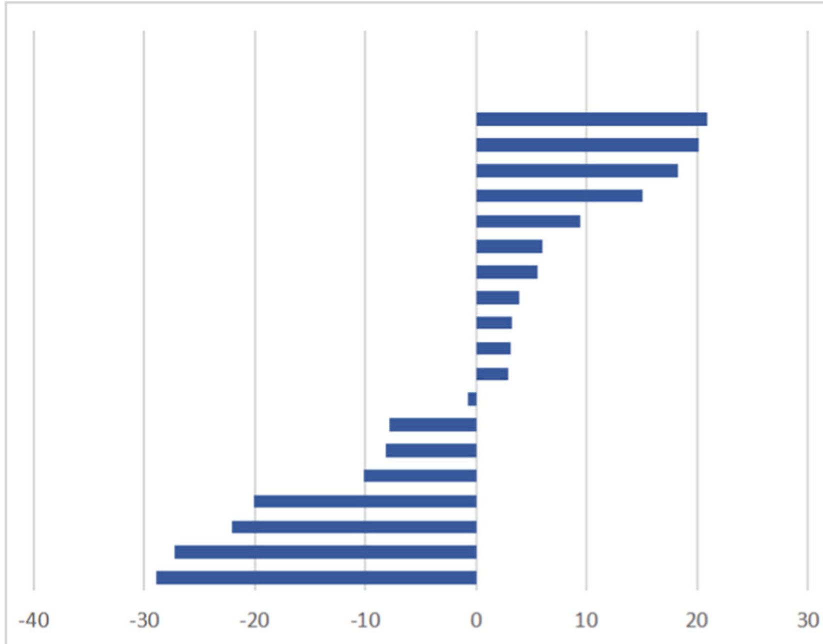


Fig. 11 Declining cities



incentives. $E(\omega - u) = -0.1917$; This indicates that the disincentives are dominant, thus indicating that the level of green technology innovation in resource-based cities is lower than the optimal level. In terms of the ratio of the inhibitory and incentive effects of environmental regulation, the inhibitory effect is 74.01% and the incentive effect is 25.99%, which explains the total variance. This indicates that the level of green technology innovation in China basically depends on environmental regulation, and the inhibitory effect dominates the combined effect. This is consistent with the previous estimation results.

Further analyzing the specific magnitudes of the bilateral and net effects of environmental regulations that deviate green technological innovation from the optimal level, and the estimated results are presented in Table 8, which yield the inhibitory effect of environmental regulations in

Fig. 12 Regenerating cities

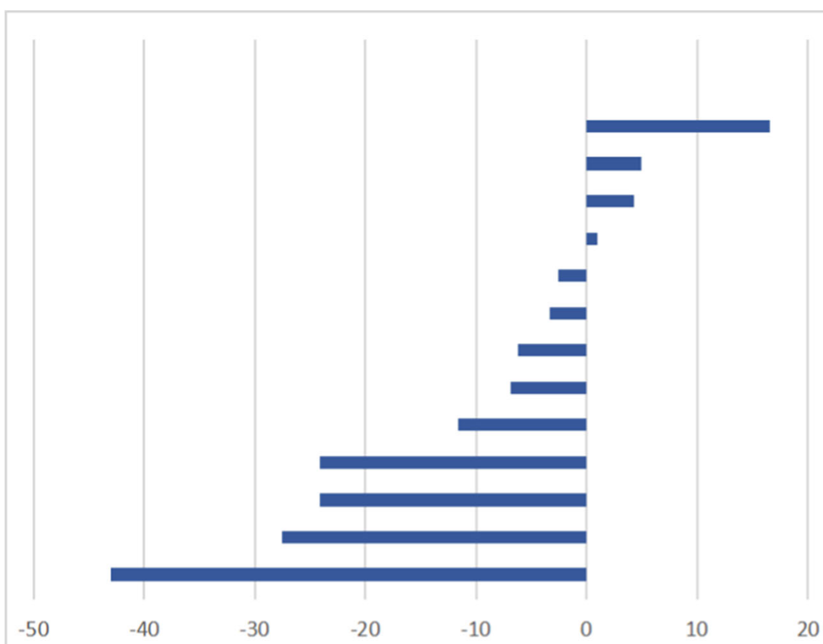


Table 7 Incentive and disincentive effects of environmental regulation

	Variable meaning	Symbol	Measurement coefficient
Bilateral effects	Random error term	σ_v	0.4397
	Cost disincentive effect of environmental regulation	σ_u	0.4705
	Innovation incentive effect of environmental regulation	σ_ω	0.2788
Variance decomposition	Total variance of the random term	$\sigma_v^2 + \sigma_u^2 + \sigma_\omega^2$	0.4925
	Weight of bilateral effects	$\frac{\sigma_u^2+\sigma_\omega^2}{\sigma_v^2+\sigma_u^2+\sigma_\omega^2}$	60.74%
	Weight of disincentive effect	$\frac{\sigma_u^2}{\sigma_u^2+\sigma_\omega^2}$	74.01%
	Weight of incentive effect	$\frac{\sigma_\omega{}^2}{\sigma_u^2+\sigma_\omega{}^2}$	25.99%

Table 8 Estimation of bilateral effects

	Mean	SD	p25	p50	p75
Environmental regulation incentive effect	21.58	9.72	15.75	18.73	24.81
Environmental regulation disincentive effect	31.89	15.74	20.67	26.85	37.73
Net effect	−10.31	22.87	−22.52	−8.37	3.75

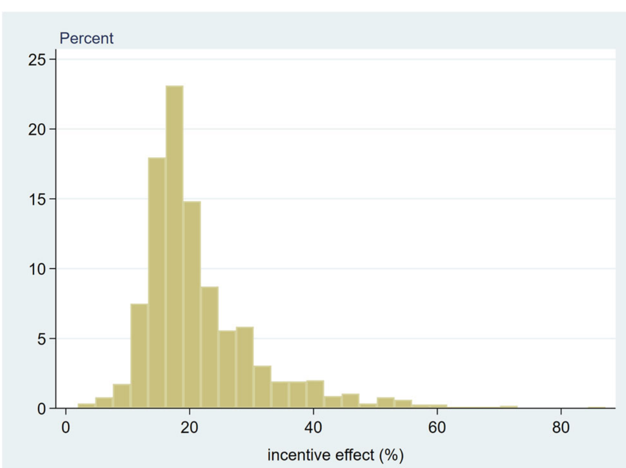


Fig. 13 Incentive

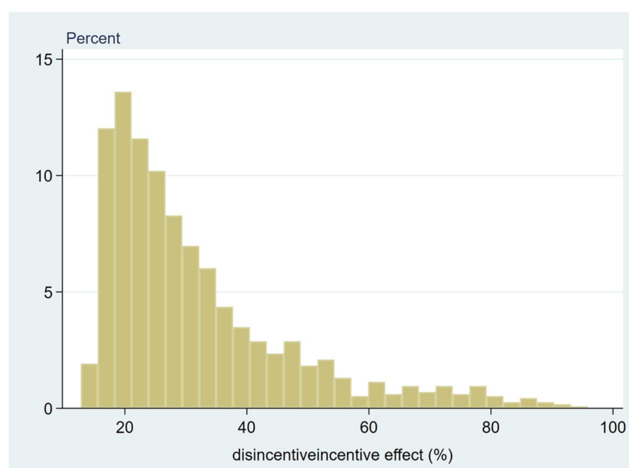


Fig. 14 Disincentive

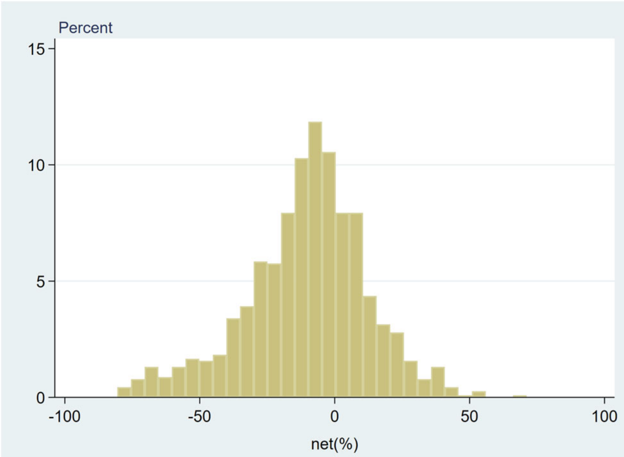


Fig. 15 Net

resource-based cities as 31.89%, the incentive effect as 21.58%, and the net effect as −10.31%. This indicates that the inhibitory effect of environmental regulation makes the level of green technology innovation lower than the optimal level of 28.63%, the incentive effect of environmental regulation makes the level of green technology innovation lower than the optimal level of 21.58%, and the combined effect of the two offsetting effects makes the level of green technology innovation lower than the optimal level of 10.31%. Table 8 shows the incentives and disincentive effects of environmental restrictions on green technology innovation at the first quartile, second quartile, and third quartile of the distribution, respectively. Furthermore, the net effect at the 75th percentile is positive 3.75, There has been a reduction in green technology innovation compared to the frontier level at the 25th and 50th percentiles. Figures 13, 14, and 15 show that both the spillover effect and the crowding-out effect show the right trailing phenomenon, and the suppression effect still exists around 95% of the trailing effect, while the spillover effect disappears around 60%. Numerically, the magnitude of the bilateral effect differs somewhat from the previous paper, but the difference is not significant. Overall, the inhibitory and incentive effects of environmental regulation co-exist, and the inhibitory effect dominates, which is consistent with the previous results and indicates the robustness of this paper's study.

Conclusion

There are two opposing views on the impact of environmental regulation on green technology innovation. The fundamental problem is that environmental regulation has two opposing effects at the same time, and the findings cannot be agreed upon by conducting unilateral studies. In this paper, we use a bilateral stochastic frontier model to decompose the bilateral effects based on dynamic panel data of 115 prefecture-level resource-based cities in China, and empirically analyze their temporal characteristics as well as the differences in the effects of different life-cycle resource-based cities. The results of the study show that:

(1) Green technology innovation in resource-based cities is subject to both innovation incentives and cost inhibiting effects of environmental regulations, and the cost inhibiting effect is dominant. In terms of the ratio of the inhibitory and incentive effects of environmental regulation, the inhibitory effect is 61.91% and the incentive effect is 38.09%, which explains the total variance. The inhibitory effect of environmental regulation in resource-based cities is 28.63%, the incentive effect is 23.83%, and the net effect is −4.8%. This indicates that the inhibitory effect of environmental regulation makes the level of green technology innovation lower than the optimal level of 28.63%, the incentive effect of environmental regulation makes the level of green technology innovation lower than the optimal level of 23.83%, and the combined effect of the two offsetting effects makes the level of green technology innovation lower than the optimal level of 4.8%.

(2) The temporal characteristics of the bilateral effects show that the dominant effects are different in different periods, and the net effect shows a "suppression-promotion" process. In the sample years, the net effect shows a decreasing trend during 2013–2014 and an increasing trend after 2015.

(3) For resource-based cities with different life cycles, the effect of environmental regulation on green technology innovation differs, and the mean value of the net effect of green technology innovation in resource-based cities is declining, mature, regenerating, and growing, in descending order.

This study proposes the following policy recommendations based on the research findings:

(1) In order to accelerate the formation of green development and achieve the dual carbon goal, the government should take the initiative to promote environmental governance and formulate reasonable environmental regulation policies to make up for the deficiencies of the market in promoting green development. Traditional non-clean technology areas of product production and technology research and development have a profit advantage, green technology innovation after the obvious disadvantage, the market alone is difficult to achieve technological progress in the green direction, so the government needs to play a guiding,

regulatory role, through the introduction of relevant environmental protection policies using administrative means to make up for the lack of market in regulating the progress of green technology.

(2) The implementation of differentiated environmental regulatory policies by region, not "one size fits all." The effect of regulation differs for resource-based cities with different life cycles, and the benefits generated are different, so the key is to grasp the balance between efficiency improvement and environmental governance. First, for declining cities, the regulation should focus on promoting the green development of successive industries, establishing deep processing of resources on the basis of extending the existing industrial chain, actively supporting the construction of green technology development projects in resource-based cities, and setting up special funds to help declining cities solve the environmental, employment, and other problems left by history. Secondly, for mature cities, the regulation policy should maintain the existing resource industries on the basis of the existing state of increasing returns to scale, avoid neglecting green technology input and development, appropriately increase the scale effect, give full play to the innovative incentive effect of regulation, overall coordinate the industrial layout, and explore green development mode. Thirdly, for regenerative cities, the regulation should focus on promoting this type of cities to get rid of the dependence on the original resources and develop competitive alternative green industry clusters. Attracting foreign investment is an effective way to do this, and foreign investment will be accompanied by the introduction of green innovative technologies. Fourthly, for growth-oriented cities, they should give play to the advantages of their resource-led industries, reasonably determine the intensity of resource development, extend their life cycle, expand their resource advantages, and promote the internalization of their environmental costs through strict cost suppression to promote the development of green technology in their industries and obtain transformational development.

Author contribution W.Y. contributed to the conceptualization, data curation, methodology, formal analysis, writing—review and editing. M.W. contributed to the visualization,writing—original draft,software, writing—review and editing. All authors have read and agreed to the published version of the manuscript.

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Data availability The data and code used in this study are available on request from the first author and corresponding author.

Declarations

Institutional review Not applicable.

Informed consent Not applicable.

Conflict of interest The authors declare no competing interests.

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