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Can Green Taxation Stimulate Green Technological Innovation for Sustainable Development in China? Evidence from Spatial Spillovers and Threshold Effects

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Abstract

Green technological innovation is widely recognized as a critical driver of sustainable development. This study examines the impact of green taxation on green technological innovation using panel data from 30 Chinese provinces from 2007 to 2022. It distinguishes between narrow and broad green taxation. Using baseline regression, spatial Durbin, and threshold models, the analysis reveals that the green tax reform significantly promotes green technological innovation. Broad green taxation has a stronger effect than narrow green taxation. Narrow green taxation shows significant spatial spillover effects. The impact of both narrow and broad green taxes on green technological innovation shows spatial heterogeneity, with the strongest main effect in the eastern regions. The threshold analysis further shows that surpassing the industrialization threshold significantly enhances green technological innovation, regardless of whether narrow or broad green taxes are used. These empirical results indicate that a differentiated green taxation can promote green technological innovation and achieve sustainable development goals. This study provides policy insights for optimizing green fiscal tools to promote innovation-driven sustainable development.

Keywords: green taxation; green technological innovation; spatial spillover; threshold effect; sustainable development

1. Introduction

Environmental protection tax is a crucial policy tool for environmental protection [1]. The Chinese environmental taxation system has undergone a significant institutional transition from “pollutant discharge fee” to “environmental protection tax.” In 2007, the Chinese government explicitly proposed studying environmental taxation as part of its strategy to establish fiscal systems conducive to scientific development, deepened reforms of the resource compensation system, and ecological compensation mechanisms. After over a decade of deliberation and revision, the Environmental Protection Tax Law formally took effect in 2018, replacing the nearly four-decade-old pollutant discharge fee system [2]. This institutional shift not only enhanced the standardization of environmental governance but also aimed to drive green transformation of economic entities through tax incentives. One core mechanism is stimulating green technological innovation.

Green technological innovation addresses environmental challenges by developing new products and processes that reduce energy consumption, waste, and pollution emis-



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sions and improve environmental management efficiency [3,4]. From a theoretical perspective, environmental protection taxes can increase the pollution costs. These higher pollution costs motivate companies to devote green development. The investment helps firms secure long-term competitive advantages and ensures they maintain compliance with regulations [5]. This facilitates technological modernization and green industrial upgrading [6,7]. However, evidence suggests that inappropriate tax burdens may suppress corporate innovation and even negatively impact short-term economic growth [8,9]. Divergent findings in existing studies may stem from a singular definition of “green taxation,” failing to distinguish between narrow and broad green taxation. This oversimplification hinders precise policy design.

China has vast regional differences in industrial structure, environmental regulation, and technology capacity. These differences create spatial spillovers and spatial heterogeneity [10]. Environmental tax effects may thus extend beyond local areas to neighboring regions. Stricter regulations in one region could relocate polluting industries to areas with laxer policies, reducing overall emission reduction efficacy. Though spatial effects of environmental regulation are widely studied [11], few works examine how narrow versus broad green taxes differentially drive green innovation across spatial dimensions. This gap limits the understanding of regional policy synergies.

As artificial intelligence emerges and industrial transformation deepens, the impact of green taxes on green technological innovation may exhibit threshold effects. Industrialization is a core process of an economy’s structural transformation. Across different stages of industrialization, systematic differences exist in energy consumption intensity, technological capacity, and the effectiveness of environmental regulations [12]. Existing threshold studies focus on green tax policy variables but overlook industrialization’s structural role. Consequently, systematic analysis of industrialization as a threshold variable remains underdeveloped, including critical threshold values and differential mechanisms across stages.

This paper examines 30 provinces in China, focusing on provincial panel data from 2007 to 2022, and comprehensively analyzes narrow and broad green taxes impact green technological innovation, considering linear, spatial, and nonlinear aspects [13,14]. The marginal contributions of this study are as follows: (1) Distinguishing between narrow and broad green taxation overcomes the limitation of using a single measure in previous studies. It reveals how different tax scopes affect green technological innovation and provides evidence for targeted policy design. (2) Comprehensively analyzing the spatial effects from broad green taxation and narrow green taxation, and conducting in-depth analyses from the perspectives of spatial spill effects and heterogeneity, fills the gap in the comprehensive spatial analysis of green taxation and innovation. (3) Combining linear, spatial, and threshold analyses provides evidence for designing region-specific environmental taxation policies.

2. Literature Review

Green taxation refers to tax policies designed to incentivize environmentally friendly behavior and discourage harmful activities [15]. Its core objective is to reduce environmental negative externalities by taxing activities that cause environmental degradation. Scholars have refined this concept, noting its evolution from a single tax instrument to a diverse strategy encompassing resource utilization and environmental protection [16–18]. Narrow green taxation denotes the environmental protection tax specifically. Broad green taxation, however, includes all resource use and environmental conservation relevant taxes. Broad green taxation spans the resource–consumption–pollution chain. It specifically encompasses taxes on resource extraction (e.g., resource tax), consumption of pollution-

intensive goods (e.g., consumption tax, vehicle purchase tax), land use (e.g., urban land use tax, farmland occupation tax), and other related activities. This multi-tax approach aims to cover environmental costs across different economic stages. [19]. This classification highlights the differing scopes of policy tools and their potentially distinct impacts on green innovation.

The Porter Hypothesis posits that well-designed environmental regulations can foster innovation. By increasing the cost of pollution, they encourage companies to develop cleaner technologies [20]. By raising the pollution fee, they encourage enterprises to create green technologies [21]. Further research has explored this link. Early empirical work by Jaffe and Palmer [22] established that environmental regulation can spur innovation while maintaining competitiveness. Popp [23] later emphasized that economic tools, such as taxes, can steer technological development toward greener solutions. Similarly, Li [24] argued that environmental taxation raises the marginal cost of pollution, altering corporate incentives and thereby driving green innovation. In addition to directly substituting old technologies, environmental taxes may create an “innovation compensation” effect.

2.1. Impact of Green Taxation on Green Technological Innovation

Green tax policies influence corporate behavior through price signals and regulatory pressure, with theoretical foundations rooted in a combination of the “Porter Hypothesis” and neoclassical economics perspectives. The imposition of green taxes markedly boosts green investment and innovation. This effect is especially pronounced among high-emission firms [25]. Xu et al. [26] noted that environmental taxes improve pollution control capacity, indirectly driving technological upgrades. Zhao et al. [27] demonstrated that environmental legislation reshapes corporate investment preferences towards eco-friendly projects. In summary, green taxes provide impetus for green technological progress by creating market incentives and guiding resource reallocation.

However, policy effectiveness may depend on its comprehensiveness. A single pollution tax may lead to the substitution or transfer of pollutants, whereas a comprehensive green tax system can provide more holistic and synergistic incentives. Research also directly confirmed that comprehensive environmental legislation accelerates corporate green innovation more effectively than single policies [28].

Based on the above theory and literature, this paper proposes the following hypotheses:

H1: *After the green tax reform, green tax policies have a better effect on promoting green technological innovation.*

H2: *Broad green taxes that promote green technological innovations are stronger than narrow green tax.*

2.2. Spatial Spillover Effects

The impact of technological innovation exhibits spatial externalities, and green technological innovation is no exception. The strength of a region’s environmental rules and its level of green innovation can influence neighboring areas. This influence operates through channels like knowledge spillover, technology diffusion, and industrial transfer [29]. As a key environmental policy tool, green tax effects also display spatial spillovers. On the one hand, stringent green taxes may prompt the transfer of local pollution-intensive industries to regions with lower environmental standards [30]. On the other hand, technological breakthroughs achieved by local firms under green tax pressure may generate positive knowledge spillovers to surrounding areas through supply chains, talent mobility, or demonstration effects. This shows that the net spatial effect of green taxation is an empirical question.

Based on the literature, this paper proposes the following hypotheses:

H3: *The impact of green taxes on green technological innovation exhibits positive spatial spillover effects.*

2.3. Heterogeneous Effects

Differences in industrial structure, technological abilities, and institutional environments among regions may lead to divergent effects of green tax policies [31]. Theoretically, the eastern region, with its more mature innovation ecosystem and stricter environmental law enforcement, equips firms with greater capacity and motivation to respond to green tax policies through technological innovation [32]. In contrast, central and western regions, often more reliant on resource-based industries and facing stronger survival pressures, may exhibit cost avoidance rather than innovation incentive in response to green taxes [33].

Based on regional heterogeneity theory, this paper proposes the following hypothesis:

H4: *The promoting effect of green taxes on green technological innovation exhibits regional spatial heterogeneity, forming the most significant main effect in the eastern region.*

2.4. Threshold Effects

The connection between taxation regulation and green innovation is complex and often nonlinear. The industrialization level, often measured by the proportion of industrial value added to GDP, is considered a pivotal threshold variable [34,35]. The characteristics and transmission mechanisms vary systematically across different stages of industrialization [36]. At the low industrialization stage, the economic structure is dominated by resource-dependent and labor-intensive traditional industries. Firms operate on thin profit margins, underinvest in R&D, and possess weak technological capabilities. At the medium industrialization stage, the industrial structure begins to upgrade towards capital-intensive and technology-intensive sectors. Firms have accumulated considerable capital and technical foundations. They possess a certain capacity to absorb costs and search for technologies. At the high industrialization stage, the economic structure transitions towards high-tech industries, advanced manufacturing, and green service-oriented sectors. Firms not only possess strong R&D capabilities and ample capital but also face intense competition and growing green market demand.

Therefore, this study proposes the following hypothesis:

H5: *As the industrialization level increases from low to high, the impact of green taxes on green technological innovation exhibits a “U-shaped” relationship, inhibiting first and promoting later.*

3. Methodology and Data

3.1. Research Flowchart

The research employs provincial panel data from 2007 to 2022 across 30 Chinese provinces, includes four parts: data collection, data processing, data analysis, and result testing and analysis. Figure 1 shows the flowchart.

3.2. Model Specification

3.2.1. Baseline Regression Model

This paper uses the baseline regression model below to identify the impact of green taxation on green technological innovation. Province and year fixed effects are controlled.

$$GTI_{it} = \beta_0 GT_{it} + \chi_0 Control_{it} + year + Province + \varepsilon_{it} \quad (1)$$

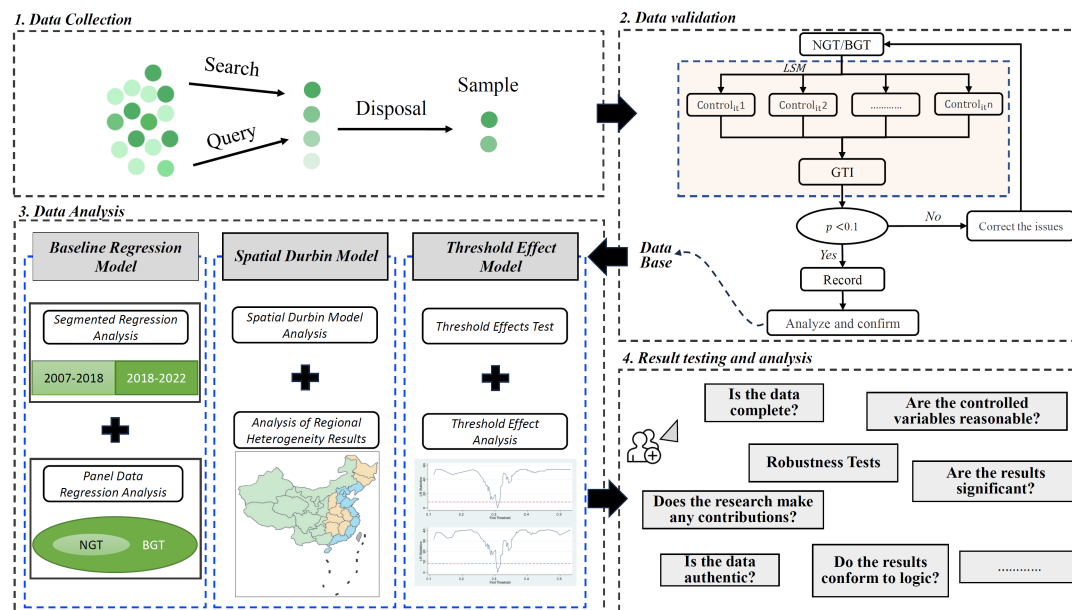


Figure 1. Research technical roadmap.

3.2.2. Spatial Durbin Model

The spatial Durbin model (SDM) constitutes an extended form integrating both spatial lag and spatial error specifications. Its defining feature lies in accounting for spatial dependence, thereby mitigating omitted variable bias that is inherent. Drawing on Elhorst [37], W_{it} is the economic-distance spatial weight matrix; the general SDM specification for panel data analysis is expressed as

$$GTI_{it} = \rho_0 \sum_{i=1}^N W_{it} GTI_{it} + \alpha_0 GT_{it} + \mu_0 \sum_{i=1}^N W_{it} GT_{it} + \omega_0 Control_{it} + year + Province + \varepsilon_{it} \quad (2)$$

3.2.3. Threshold Effect Model

Following Hansen [38], the panel threshold regression model is specified as follows (illustrating a single threshold as an example):

$$GTI_{it} = \gamma_1 GT_{it} \cdot I(IND_{it} \leq \delta_1) + \gamma_2 GT_{it} \cdot I(\delta_1 < IND_{it} \leq \delta_2) + \gamma_{n-1} GT_{it} \cdot I(\delta_{n-1} < IND_{it} \leq \delta_n) + \dots + \gamma_n \gamma_{n-1} GT_{it} \cdot I(IND_{it} > \delta_n) + \sigma_1 Control_{it} + \varphi_0 + \varepsilon_{it} \quad (3)$$

3.3. Variable Definitions

3.3.1. Green Technological Innovation

Following the methodological approaches of Su and Moaniba [39], Hu [40], and Liu [41], this study measures green technological innovation using patent counts for environment-related technologies. Specifically, prefectural-level green patent data from the CNRDS-Green Patent Database were aggregated into provincial-level datasets. Provincial green patent applications refer to the sum of applications for green invention patents and utility model patents. The dependent variable is the natural logarithm of total provincial green patent applications. The patent granting process involves lengthy and uncertain examination periods and may be influenced by non-technical administrative factors, whereas application data reflect innovators' autonomous efforts and technological output tendencies more stably [42]. Therefore, green patent applications provide a more direct and timely measure of innovation activity in green technology fields, which is consistent with mainstream research practices.

3.3.2. Green Taxation

In this study, green taxation is measured using both narrow and broad definitions, following the classification framework of Yang [43]. Narrow green taxation directly targets pollutant emissions, measured by provincial-level environmental protection tax revenue. Prior to the formal implementation of this tax in 2018, pollutant discharge fees served as a consistent proxy.

Broad green taxation reflects a multi-tax governance approach that covers the entire lifecycle from resource extraction to consumption and emission [44]. Based on the existing literature, it includes eight tax categories. Although these taxes operate through different mechanisms, they jointly form a comprehensive green tax system that regulates resource use, production, consumption, and post-pollution treatment. Aggregating them into one broad measure captures the overall policy intensity of green fiscal governance. The paper calculates the broad green taxation variable by summing the revenues of these eight taxes at the provincial level and then taking the natural logarithm.

3.3.3. Control Variable

This study controls a set of factors that may also influence green technological innovation. The urbanization level (URB) is measured by the proportion of urban population to the total population. Human capital (HUM) is proxied by the proportion of college students within the total population. Fiscal support intensity (ESF) is calculated as the ratio of public budget expenditure to GDP. Furthermore, industrial structure (IS) indicates economic upgrading, measured by the ratio of the tertiary sector to the secondary sector. R&D intensity (RD) is the internal R&D spending over GDP. Technology market development (TMDL), defined as technology transaction value over GDP. The per-capita economic level (PGDP) is the economic development level. The informatization level (INFORM) is the share of postal and telecom revenue in GDP. The transport infrastructure level (TRSPORT) is measured by the natural logarithm of freight volume.

3.3.4. Threshold Variable

The industrialization level (IND) is used as a threshold variable, quantified as the proportion of industrial value-added in regional GDP [45]. The response of firms to environmental taxes varies with the economy's dependence on industrial activities. Therefore, the impact of green taxation on green innovation may vary across different stages of industrial development. Following the threshold regression method [46], this study allows the impact of green taxation to change between low-industrialization and high-industrialization regimes.

This study conducts multicollinearity diagnostics, and the results show that all variance inflation factor (VIF) values are well below the conventional threshold, indicating that multicollinearity is not a concern. Detailed definitions of each variable are provided in Table 1.

Table 1. Variable definitions and measurement.

Variable Type	Variable	Variable Definition	Variable Measurement
Dependent Variable	GTI	Green technological innovation	ln(Green patent applications)
	NGT	Narrow green taxation	ln(1 + Environmental Protection Tax)
Independent Variable	BGT	Broad green taxation	ln(1 + $\sum$ [Resource Tax, EPT, Urban Maintenance and Construction Tax, Land Use Tax, Vehicle/Vessel Tax, Farmland Tax, Consumption Tax, Vehicle Purchase Tax])

Table 1. *Cont.*

Variable Type	Variable	Variable Definition	Variable Measurement
Control Variable	URB	Urbanization level	Urban population/Total population
	HUM	Human capital level	College students/Total population
	ESF	Fiscal support intensity	General budget expenditure/GDP
	IS	Industrial structure	Tertiary Industry Output/Secondary Industry Output
	RD	R&D intensity	Internal R&D expenditure/GDP
	TMDL	Technology market development	Technology transaction value/GDP
	PGDP	Economic development level	Per capita GDP
	INFORM	Informatization level	Postal and telecom revenue/GDP
	TRSPORT	Transport infrastructure level	ln(Freight volume)
Threshold Variable	IND	Industrialization level	Industrial value-added/GDP

3.4. Data Source and Data Sample

China initiated comprehensive environmental tax research in 2007, proposing institutional frameworks and policy reforms. Accordingly, this study employs provincial panel data from 2007 to 2022 across 30 Chinese provinces, excluding the Tibet autonomous region, Hong Kong, Macau, and Taiwan.

To measure green technological innovation, this study employs indicators from the China Research Data Service Platform (CNRDS). The relevant taxation data come from the China Tax Yearbook and the Provincial Statistical Yearbooks. All other variables are obtained from the China Statistical Yearbook and Provincial Statistical Yearbook. The descriptive statistics for each variable are presented in Table 2.

Table 2. Descriptive statistics.

Variable	Observations	Mean	Standard Deviation	Min.	Max.
GTI	480	7.592	1.575	3.434	10.761
NGT	480	1.718	0.679	0.28	3.356
BGT	480	6.172	0.886	3.334	7.666
URB	480	0.576	0.133	0.323	0.893
HUM	480	0.02	0.007	0.007	0.044
ESF	480	0.246	0.108	0.097	0.758
IS	480	1.265	0.699	0.561	4.894
RD	480	0.017	0.011	0.004	0.057
TMDL	480	0.015	0.026	0	0.15
PGDP	480	10.664	0.582	9.331	12.009
INFORM	480	0.064	0.048	0.015	0.29
TRSPORT	480	11.509	0.848	9.311	12.903

The data processing procedure followed two critical steps: (1) A winsorizing procedure was implemented to cap extreme values in the dataset. All continuous variables were winsorized at the 1% and 99% levels to reduce the influence of outliers on the estimation. (2) Pollution discharge fees were adopted as the proxy for narrow green taxation prior to 2018, when Chinese environmental protection tax law took effect. Missing narrow

green taxation values during 2016–2018 were imputed via linear interpolation, ensuring a continuous time series for analysis.

4. Research Analysis and Discovery

4.1. Baseline Regression Analysis

4.1.1. Segmented Regression Analysis

In the model tests, both the Hausman test and the F-test are significant at the 1% level, so the fixed effects model is more appropriate. To verify the effects of green taxation on green technological innovation, this study conducted segmented regressions with 2018 as the breakpoint. This approach compares the regression outcomes before and after 2018 to evaluate the policy transition effects.

In Table 3, column (1) reports the impact of narrow green tax on green technological innovation before 2018, and column (2) reports the impact after 2018, respectively. Specifically, the coefficient for narrow green taxation is negative and insignificant in column (1), but positive and significant at the 1% level in column (2). This indicates that during the pollutant discharge fee period, the collection standards were relatively low and enforcement varied across regions. The environmental protection tax reform fundamentally transformed the role of narrow green taxation by establishing a credible, stringent, and legally binding cost signal. This shift effectively activated the innovation compensation mechanism postulated by the Porter Hypothesis. Hypothesis 1 is supported.

Table 3. Segmented regression analysis results.

Variable	(1)	(2)
	GTI	GTI
NGT	−0.0421 (−0.64)	0.1277 *** (2.66)
Observations	330	150

Note: Heteroskedasticity-adjusted t-statistics are reported in parentheses. Asterisks *** denote statistical significance at the 1% level.

4.1.2. Panel Data Regression Analysis

This study employs panel data regression analysis for the core variables. As presented in Table 4, columns (1) report narrow green taxation significantly. As presented in Column (2), broad green taxation is also significant and has a more pronounced effect on the promotion of green technological innovation than narrow green taxes. This enhanced effect may arise because broad green taxation encompasses a broader spectrum of taxes and policies related to green development, imposing more comprehensive constraints and incentives on corporate production and operational activities. Therefore, Hypothesis 2 is supported.

Table 4. Panel data regression analysis results.

Variable	(1)	(2)
	GTI	GTI
NGT	0.128 *** (2.86)	
BGT		0.573 *** (9.43)
Observations	480	480

Note: Heteroskedasticity-adjusted t-statistics are reported in parentheses. Asterisks *** denote statistical significance at the 1% level.

4.2. Spatial Durbin Model Analysis

Before conducting spatial econometric regression, this study performed a Lagrange multiplier (LM) test to detect spatial effects in the variables, then applied likelihood ratio (LR) and Wald tests to determine the model. The test results are shown in Table 5. The spatial Durbin model should be used to analyze the spatial effects.

Table 5. Spatial econometric model specification test results.

Test	NGT Statistic	<i>p</i> -Value	BGT Statistic	<i>p</i> -Value
LM-error	39.020	0.006	57.908	0.000
LM-lag	69.827	0.000	73.133	0.000
Robust LM-error	7.668	0.006	21.679	0.000
Robust LM-lag	38.475	0.000	36.904	0.000
LR test (SDM and SAR)	38.99	0.0000	21.91	0.0111
LR test (SDM and SEM)	35.75	0.0001	23.26	0.0098
Wald test (SDM and SAR)	41.39	0.0000	23.60	0.0087
Wald test (SDM and SEM)	37.58	0.0000	23.95	0.0077

As presented in Table 6, the main effect coefficients for both narrow green taxation and broad green taxation are significantly positive. This indicates that both types of green taxation effectively stimulate green technological innovation within their respective local regions. The narrow green taxation's spatial lag term coefficient is significantly positive. This suggests that an increase in narrow green taxation levels in neighboring regions positively influences local green technological innovation. The spatial lag effect of broad green taxation is not statistically significant. The spatial rho coefficients of narrow green taxation and broad green taxation are significantly negative, indicating negative spatial dependence in green technological innovation across regions. This reflects a competitive suppression effect, where innovation in one region may inhibit innovation in neighboring regions.

Table 6. Spatial Durbin analyses.

Variable	(1) GTI	(1) GTI
NGT Main Effect	0.199 *** (5.23)	
BGT Main Effect		0.336 *** (4.49)
NGT Spatial Spillover Effect	0.634 *** (2.60)	
BGT Spatial Spillover Effect		1.075 (1.60)
NGT Spatial Rho	−0.625 *** (−2.77)	
BGT Spatial Rho		−0.455 ** (−2.10)
Observations	480	480

Note: Heteroskedasticity-adjusted t-statistics are reported in parentheses. Asterisks ** and *** denote statistical significance at the 5%, and 1% levels.

For the effect decomposition presented in Table 7, the decomposed main effects for both narrow green taxation and broad green taxation remain significantly positive, confirming their local incentive effect. The decomposed indirect effect is significantly positive for narrow green taxation but is not significant for broad green taxation. Hypothesis 3 is partially supported.

Table 7. Spatial Durbin model decomposition.

Variable	LR Direct		LR Indirect		LR Total	
	(1)	(2)	(3)	(4)	(5)	(6)
NGT	0.189 *** (4.71)		0.327 ** (2.04)		0.516 *** (3.31)	
BGT		0.322 *** (4.28)		0.661 (1.34)		0.984 * (1.94)
Number of Observations	480	480	480	480	480	480

Note: Heteroskedasticity-adjusted t-statistics are reported in parentheses. Asterisks *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively.

The decomposed indirect effect for narrow green taxation is significantly positive. This occurs because narrow green taxation specifically targets environmental pollution with clear policy objectives. Overall, it generates positive spatial spillovers such as technology diffusion, knowledge transfer, or competition effects on neighboring regions. The indirect effect for broad green taxation is not significant. This is likely because broad green taxation policies are more comprehensive. Their incentive signal for corporate innovation across regions is less clear and intense compared to narrow taxation. This leads to insufficient strategic cross-regional responses from firms and no significant spillover.

4.3. Regional Heterogeneity Analysis

To further analyze the spatial spillover effects revealed by the Durbin model, this study divides 30 provinces into three regions [43] and analyses the impact within each respective region.

Regional heterogeneity analysis results for narrow green taxation are shown in Table 8. Narrow green tax's main effect is significantly positive in the east, indicating effective local innovation incentives where economic development is higher and environmental regulation enforcement is stronger. It is significantly negative in the central region, likely due to industrial transition pressures causing firms to perceive the tax as a short-term cost burden, suppressing innovation investment. It is insignificant in the west, potentially related to weaker infrastructure and insufficient innovation factors. Narrow green tax's spatial lag effect is insignificant within the regions. Combined with the national spatial Durbin results, this represents the substantial economic differences between the eastern and central–western regions nationally, driving the observed national spillover.

Table 8. Regional heterogeneity analysis results for narrow green taxation.

Variable	Main			Spatial Spillover		
	(1)	(2)	(3)	(4)	(5)	(6)
Eastern	0.207 ** (2.44)			0.727 (1.14)		
Central		−0.230 ** (−2.38)			−0.164 (−0.21)	
Western			−0.008 (−0.09)			−0.813 (−1.04)
Observations	480	480	480	480	480	480

Note: Heteroskedasticity-adjusted t-statistics are reported in parentheses. Asterisks ** denote statistical significance at the 5% level.

Regional heterogeneity analysis results for broad green tax are shown in Table 9. Broad green tax's main effect is consistent with narrow taxation. However, broad green tax's spatial lag effect is significantly positive within the eastern region. Combined with the national SDM result (insignificant spillover nationally), this highlights the severe economic disparity between eastern China and the central–western regions. Broad green

taxation is more comprehensive in its policy scope. Its incentive signal for corporate innovation is less clear and less intense across regions at the national level. Therefore, it does not show significant spatial spillover effects nationally. However, the eastern region is more sensitive to policy. When the eastern region implements broad green taxation, it significantly promotes green technological innovation in neighboring regions. So, broad green taxation only has spillover effects in the eastern region. This once again reflects the regional differences in China.

Table 9. Regional heterogeneity analysis results for broad green taxation.

Variable	Main			Spatial Spillover		
	(1)	(2)	(3)	(4)	(5)	(6)
Eastern	0.157 *** (2.75)			1.044 * (1.93)		
Central		−0.136 *** (−3.38)			−0.123 (−0.28)	
Western			0.129 ** (2.52)			−0.247 (−0.67)
Observations	480	480	480	480	480	480

Note: Heteroskedasticity-adjusted t-statistics are reported in parentheses. Asterisks *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively.

Therefore, Hypothesis 4 is supported. The results show that the impact varies considerably across regions: it is positive and pronounced in the east, negative in the central region, and statistically insignificant in the west. Additionally, within the eastern region, broad green taxation generates a positive spillover effect on neighboring provinces. Considering China's uneven regional development, green taxes' innovation effect may be distinct based on thresholds of industrial progress.

4.4. Threshold Analysis

To further explore the heterogeneous impact of green taxation on green technological innovation, this study processes the threshold effect analysis. With industrial transformation, there has been a threshold effect of the industrialization level on the innovation effect of green tax over the years. The industrialization level is the threshold variable. This choice is based on the well-documented existence of significant regional disparities in industrialization levels. As shown in Table 10, the threshold test results identify single, not multiple, threshold effects for green taxation.

Table 10. Threshold effect test results.

Independent Variable	Threshold	p Value	F-Statistic	Crit10	Crit5	Crit1
NGT	Single	0.0060	55.75	32.9535	38.2935	46.2501
	Double	0.5910				
	Triple	0.3820				
BGT	Single	0.0400	41.75	32.3305	38.7101	55.3795
	Double	0.8070				
	Triple	0.5760				

Note: The number of bootstrap samples is 1000.

This study conducts single-threshold analyses for both narrow green taxation and broad green taxation. The LR statistical charts of the threshold effects of narrow green taxation and broad green taxation are plotted in Figures 2 and 3 respectively. The estimated threshold value for the industrialization level is identical for both variables at 0.3085, classifying the sample into two regimes. The 95% confidence interval ([0.3052, 0.3111]) exhibits narrow bounds, confirming high precision in threshold estimation. This demonstrates that

the industrialization level significantly moderates the relationship between green taxation and green technological innovation.

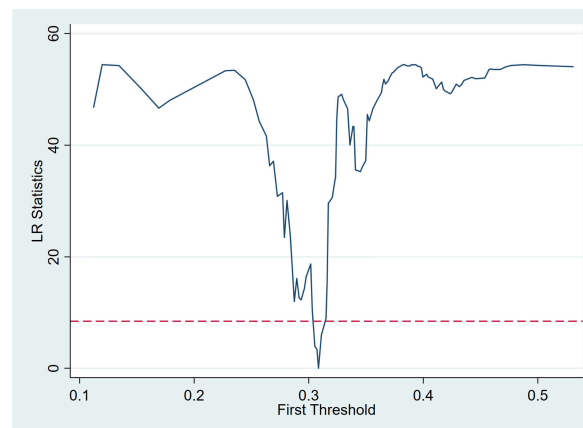


Figure 2. The LR statistical charts of NGT.

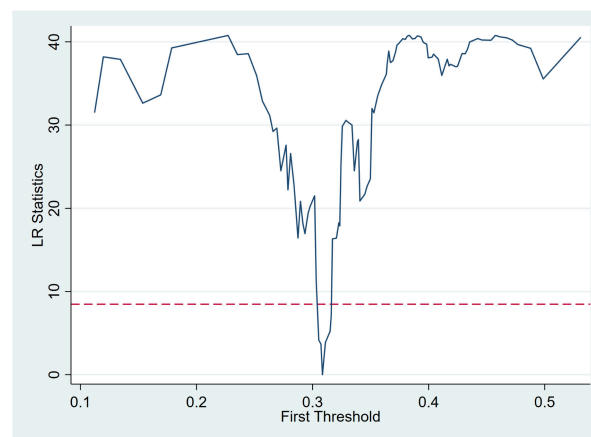


Figure 3. The LR statistical charts of BGT.

This threshold has clear economic significance: when the industrialization level is below 0.3085, the economy is in the early or middle stage of industrialization, with a relatively limited industrial scale, and green taxation policies have not yet significantly incentivized corporate innovation behavior. When the industrialization level exceeds this threshold, the economy enters a later or advanced stage of industrialization, characterized by a more mature industrial system, where green taxation can more effectively stimulate green technological innovation through cost internalization and innovation compensation effects.

Columns (1) and (2) show that narrow green taxation fails to exhibit a statistically significant influence on innovation where industrialization is low in Table 11. Above the threshold, its impact turns positive and becomes markedly stronger. Columns (3) and (4) indicate that broad green taxation already has a significant positive effect in low-industrialization areas, and this effect is amplified in high-industrialization contexts. In summary, the threshold effect of the industrialization level is monotonically positive, not U-shaped. Below the threshold, broad green taxation yields superior innovation stimulation; above the threshold, both narrow green taxation and broad green taxation significantly enhance green technological innovation outcomes. Consequently, Hypothesis 5 is rejected.

Table 11. Threshold effect regression results.

Variable	(1)	(2)	(3)	(4)
	GTI	GTI	GTI	GTI
NGT	0.044 (0.49)	0.183 *** (3.40)		
BGT			0.384 *** (2.90)	0.481 *** (7.29)
Number of Observations	141	339	141	339

Note: Heteroskedasticity-adjusted t-statistics are reported in parentheses. Asterisks *** denote statistical significance at the 1% level.

Although theoretical reasoning supports a U-shaped relationship, in China's current development stage, dominated by medium–high industrialization, the promoting effect of green taxation on green technological innovation has become dominant, presenting a monotonically positive impact. Otherwise, China's green finance and innovation subsidies policy has improved significantly, alleviating the cash-flow pressure imposed by green taxation. The inhibitory effect of green taxation has become less pronounced. This reflects the synergistic evolution between the Chinese industrialization process and environmental policy, offering policy insights for other developing countries.

4.5. Robustness Tests

Three robustness checks are conducted to validate the empirical results. The first test omits the human capital variable to assess result sensitivity. The second trims the sample period by dropping data from the crisis year 2008, thereby isolating effects from major economic shocks. The third replaces the measure of green technological innovation with applications for green utility model patents. The outcomes are summarized in Table 12.

Table 12. Robustness check.

Independent Variable	Variable	(1) Adjust Control Variable	(2) Adjust Sample	(3) Adjust Dependent Variable
NGT	Main Effect	0.183 *** (4.74)	0.190 *** (4.88)	0.268 *** (6.06)
	Spatial Spillover Effect	0.675 *** (2.72)	0.626 ** (2.53)	0.837 *** (2.97)
	Direct Effect	0.171 *** (4.14)	0.180 *** (4.36)	0.260 *** (5.68)
	Indirect Effect	0.365 ** (2.17)	0.312 ** (1.97)	0.592 ** (2.41)
BGT	Main Effect	0.324 *** (4.15)	0.303 *** (3.85)	0.172 * (1.95)
	Spatial Spillover Effect	1.350 ** (2.03)	0.967 (1.38)	2.865 *** (3.63)
	Direct Effect	0.303 *** (3.69)	0.289 *** (3.63)	0.157 * (1.69)
	Indirect Effect	0.832 * (1.78)	0.552 (1.14)	2.554 *** (3.00)
Observations		480	450	480

Note: Heteroskedasticity-adjusted t-statistics are reported in parentheses. Asterisks *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively.

For narrow green taxation, there is no substantial change. This fully shows that the regression results for narrow green taxation have good robustness. For broad green taxation, the main effect and the direct effect remain stable in direction and significance. The spatial spillover and the indirect effect become significant in some models, but their sign direction is always positive. This is consistent with the baseline regression, and there is no directional reversal. In summary, although the significance of the spatial spillover effect of broad green

taxation fluctuates across different robustness tests, the sign directions of all effects for both narrow and broad green taxation are consistent with the results. There is no substantial change. This fully shows that the research conclusions are scientific and reasonable.

5. Conclusions and Policy Recommendations

5.1. Main Conclusions

This study examines 30 provinces in China from 2007 to 2022, comprehensively employing linear, spatial, and nonlinear impacts of narrow and broad green taxes on green technological innovation. The primary findings are as follows:

Green taxation significantly incentivizes local green technological innovation. Both narrow green taxation and broad green taxation exhibit statistically significant positive direct effects. This supports the Porter Hypothesis regarding the innovation-inducing effect of appropriate environmental regulation. This study reveals that broad green taxation exhibits statistically significant positive direct effects. This supports that Porter's innovation-promoting effect is stronger than narrow green taxation's. This may stem from broad green taxation's broader tax mix imposing more systemic constraints and guidance on firms' production chains and strategic decisions.

Significant differences exist in spatial spillovers between narrow green taxation and broad green taxation. Nationally, both narrow and broad green taxation significantly promote local green innovation, with their direct effects (main effect) positive and significant at the 1% level. This confirms the fundamental mechanism where green taxes incentive green R&D by reducing innovation costs and increasing expected returns. However, regarding spatial spillovers, the spatial lag coefficient for narrow green taxation is significantly positive, indicating positive cross-regional spillover effects. In contrast, broad green taxation's spatial spillover effect is insignificant, potentially due to its comprehensive policy objectives diluting firms' clear response to cross-regional policy signals. The results align more with "competitive imitation" or "knowledge spillover" effects, where stringent narrow green taxation policies in neighboring regions stimulate local green innovation through technology demonstration, talent mobility, or market competition.

The effectiveness of green taxation exhibits significant regional heterogeneity, highly dependent on industrial structure, and resource endowment. Narrow green taxation and broad green taxation's direct effects are significantly positive in the east, significantly negative in the central region, and insignificant in the west. This verifies that the Porter Hypothesis requires specific conditions; environmental regulation effectively induces innovation compensation in developed, innovation-capable regions like the east. In regions facing industrial transition pressures like the central region, firms may perceive taxes purely as compliance costs in the short term, crowding out innovation investment. Furthermore, narrow green taxation's spatial spillover effect is only significant nationally across regions, not within the three major regions. This suggests that its spillover relies primarily on close economic linkages (e.g., industrial division, factor mobility) between the east and central-west, rather than mere geographical proximity. Broad green taxation shows not only a significant direct effect but also positive intra-regional spatial spillovers in the east; however, its national spillover effect is insignificant. This indicates that the complexity and high implementation threshold of broad green taxation may lock its positive effects within developed regions with mature institutions, infrastructure, and market systems, hindering effective diffusion to less developed central and western regions.

The industrialization level is a key threshold variable moderating the innovation effect of green taxation, with dynamic differences between the two tax types. In regions with industrialization levels lower than 0.3085, broad green taxation still provides a significant positive incentive, while narrow green taxation's effect is insignificant. This may be because

broad green taxation, through its multi-tax approach, more comprehensively internalizes environmental costs, compelling firms along the supply chain to upgrade technology. Its mechanism relies more on the macro policy framework than on firms' immediate innovation capacity. After industrialization levels surpass 0.3085, narrow green taxation's promoting effect becomes significant and strong, reflecting the capability and supply chain resilience of firms within mature industrial systems to transform explicit environmental tax burdens into drivers for technological innovation.

5.2. Policy Recommendations

Based on the research findings, this study proposes the following multi-dimensional policy recommendations.

First, the results show that broad green taxation has a stronger direct positive effect on green technological innovation than narrow green taxation. This suggests that policymakers should not rely solely on the environmental protection tax. Instead, they should coordinate it with other green-related taxes to build a more comprehensive green tax framework. However, regional heterogeneity must be considered. In the central region, both tax types exert significantly negative direct effects, so a comprehensive green tax framework cannot simply be imposed there. When introducing broad green taxation in the central region, governments need to pair it with innovation subsidies and transitional support to offset the short-term cost burden. In the western region, where the direct effects are insignificant, broad green taxation is a more suitable starting tool than narrow green taxation.

Additionally, the threshold analysis shows that in areas with industrialization below 0.3085, broad green taxation still significantly promotes innovation while narrow green taxation does not. Therefore, in less industrialized areas, broad green taxation should be the primary instrument to guide firms toward green innovation early in their development.

Second, significant spatial spillovers and regional heterogeneity call for regionally differentiated tax strategies. Narrow green taxation generates positive cross-regional spatial spillovers at the national level, indicating that stringent narrow green tax policies in the developed eastern region can stimulate green innovation in the vicinity zone through interregional linkages. Thus, rather than directly raising narrow green tax rates in the central and western zones, the government should strengthen technology transfer platforms and industrial collaboration between the eastern region and less developed areas, allowing the eastern region's policy spillovers to take effect. Within the eastern region itself, broad green taxation shows positive intra-regional spatial spillovers, which can be reinforced by maintaining strict green taxation and fostering regional innovation clusters. For the central region, given its negative direct effects, direct tax increases should be avoided; instead, policies should prioritize innovation incentives and technical assistance channels from the eastern region. For the western region, where direct effects are insignificant, policy efforts should primarily rely on broad green tax instruments and the spillover channels connected to the east.

Third, the threshold analysis shows that in areas with industrialization below 0.3085, broad green taxation still significantly promotes innovation while narrow green taxation does not. Therefore, in less industrialized areas, broad green taxation should be the primary instrument to guide firms toward green innovation early in their development. Once industrialization surpasses this threshold, narrow green taxation can be strengthened because its innovation-promoting effect becomes significant and strong at that stage. In heavy industrial zones that have crossed the threshold, governments can moderately increase narrow green tax rates, but this must be accompanied by a concrete innovation reward system. A portion of the tax revenue should be earmarked for green research and development grants, ensuring that the tax burden is directly converted into firms'

innovation capacity rather than becoming a pure compliance cost. Such a pairing makes the policy targeted and avoids the uniformly negative effects observed in the central region when taxes are raised without supporting measures.

5.3. Future Research

While this study yields significant findings, limitations exist and point to future research directions: The reliance on provincial-level macro data reveals regional patterns and spatial linkages but cannot directly identify or test micro-level mechanisms at the firm level. Therefore, future research should utilize firm-level data to validate these mechanisms, enabling a finer examination of how corporate strategies and behaviors contribute to broader sustainability goals. Additionally, extending the analysis to explore sector-specific or firm-heterogeneous effects would help design more targeted green fiscal policies, thereby accelerating the transition towards a more sustainable and innovation-driven economy.

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