

Article

The Impact of the Service Trade Innovative Development Pilot Policy on Pollution Reduction and Carbon Reduction

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Abstract

The service sector plays a central role in steering the economic structure toward greener development, and service trade provides an important route for achieving pollution reduction and carbon reduction. Drawing on a city-level panel of 278 Chinese cities from 2011 to 2022, this study uses Staggered DID and Spatial DID models to evaluate the direct and spatial spillover effects of the Service Trade Innovative Development Pilot Policy (STIDPP) on pollution reduction and carbon reduction. The results show that: (1) The STIDPP significantly promotes pollution reduction and carbon reduction, and this finding remains robust after placebo tests, PSM-DID estimation, checks addressing heterogeneous treatment effects, and controls for other policy shocks. (2) The mechanism analysis shows that the STIDPP mainly promotes pollution reduction and carbon reduction through industrial structure upgrading, green technological innovation, environmental governance investment, and public environmental concern. (3) The positive effects of the STIDPP are more pronounced in cities with higher levels of economic development, larger city size, and service-oriented industrial structures, but its promoting effect on carbon-reduction efficiency is relatively weaker in regions with stronger environmental regulation. (4) The STIDPP generates significant spatial spillover effects on pollution reduction and carbon reduction. As geographic distance increases, these effects shift from negative to positive and eventually become statistically insignificant. This study extends the research on the environmental effects of service trade and provides theoretical support and practical guidance for developing a green service trade system and enhancing the synergy between pollution reduction and carbon reduction.

Keywords: service trade; pollution reduction; carbon reduction; spatial spillover effect



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1. Introduction

China's rapid economic expansion has been accompanied by persistent pressure to reconcile growth objectives with environmental constraints. A growth pattern long associated with intensive energy use and high emissions has generated serious environmental pressures, weakening the sustainability of economic growth and creating risks for ecological security and public health. In this context, coordinated pollution reduction and carbon reduction have become central to China's efforts to transform its economy toward a greener and more sustainable trajectory. Pollution control and carbon mitigation are closely connected because they often share policy targets, technological routes, and governance instruments. Building on this, related studies have systematically assessed the synergistic effects of China's carbon reduction policies and air pollution control policies [1], revealing their multiple benefits for improving air quality and protecting public health [2].

Some studies have further clarified the practical characteristics of China's pollution reduction and carbon reduction through international comparisons [3], and proposed that carbon–pollution–ecology multi-dimensional coordination is the future direction [4].

In the context of an open economy, service trade is not only an important carrier for achieving sustainable development [5], but also a key variable for promoting pollution reduction and carbon reduction. On the one hand, the service sector has relatively low resource dependence and generates fewer pollutants and carbon dioxide [6]. On the other hand, service trade facilitates the introduction of advanced international green technologies and management practices, which reduces energy intensity and enhances green production efficiency, thereby effectively accelerating the process of pollution reduction and carbon reduction [7]. Empirical studies based on cross-country panel data show that the development of service trade can effectively promote carbon reduction and improve carbon efficiency [8,9]. Reducing service trade barriers can effectively improve the environmental performance of economies such as OECD countries [10]. As an emerging form of service trade, digital service trade has attracted considerable attention for its carbon reduction effects, and its positive impact on the carbon emission efficiency of the tourism industry has been confirmed [11]. Some studies suggest that the effect of digital service trade on carbon emissions may be nonlinear [7], and that industrial agglomeration and carbon emission trading play important moderating roles in this process [12]. In the literature on the pollution reduction and carbon reduction effects of trade policies, existing studies have largely focused on the establishment of Free Trade Zones. Evidence shows that these zones have positive effects on urban sustainable growth [13], high-quality economic development [14], and green high-quality development [15]. Some studies further indicate that Free Trade Zones significantly promote green technological innovation and enhance its efficiency [16,17], thereby providing technological support for pollution reduction and carbon reduction and facilitating firms' transition toward greener practices [18]. Research on STIDPP remains relatively limited. Existing studies indicate that STIDPP can significantly promote carbon reduction [19], improve carbon total factor productivity [20], and exert a positive impact on urban environmental performance [21]. In addition, this policy also plays an important role in promoting the green transformation of energy consumption structure [22].

Overall, the literature has identified several determinants of pollution reduction and carbon reduction and has begun to recognize the environmental relevance of service trade. However, there are still some gaps in relevant research: On the one hand, most studies only examine the impact of service trade on carbon reduction, while ignoring its positive role in pollution reduction. On the other hand, regarding trade policies, previous research has largely concentrated on Free Trade Zones, while the specific effects of the STIDPP on pollution reduction and carbon reduction have received limited attention. Furthermore, as regional economic integration deepens, pollution reduction and carbon reduction exhibit significant spatial correlation [23]. Nevertheless, the spatial spillover effects of STIDPP have rarely been examined. Given these considerations, this study employs staggered DID and spatial DID models to investigate the impact and spatial spillover effects of the STIDPP on pollution reduction and carbon reduction. This study contributes to the literature in two ways. First, it moves beyond a single carbon indicator and evaluates the STIDPP using three outcomes: pollution-reduction efficiency (PRE), carbon-reduction efficiency (CRE), and the synergy between pollution reduction and carbon reduction (PCE). Second, it identifies how the policy's spillover effects vary with distance, thereby clarifying the spatial boundary within which service-trade policy affects regional environmental outcomes. These findings provide empirical evidence for strengthening cross-regional cooperation

in service trade and promoting the coordinated governance of pollution reduction and carbon reduction.

2. Policy Background and Theoretical Analysis

2.1. Policy Background

The STIDPP has evolved through three rounds of pilot implementation since 2016, with each round expanding the scope of service-trade reform and institutional innovation. The first round began in 2016 and covered 10 provinces and cities, including Tianjin, Shanghai, Hainan, Shenzhen, Hangzhou, Wuhan, Guangzhou, Chengdu, Suzhou, and Weihai. The program also covered five national-level new areas: Harbin New Area, Jiangbei New Area, Liangjiang New Area, Gui'an New Area, and Xixian New Area. This stage focused on improving administrative systems, expanding the opening of the service sector, fostering market entities, innovating development models, and enhancing trade facilitation. Its objective was to generate institutional innovations that could be replicated and promoted on a broader scale. The second stage involved a deepening of the pilot program. In 2018, Beijing, Xiong'an New Area, and other regions were incorporated into the program, expanding its coverage to 17 provinces and cities. Building on the reforms introduced during the initial stage, this phase placed greater emphasis on both inward and outward opening of the service sector, as well as the development of digital service trade and service outsourcing. Policy support was further strengthened through measures related to taxation, finance, and public service platforms. The third stage marked the comprehensive deepening of the pilot program. In 2020, its coverage was further expanded to 28 provinces and cities. This phase placed greater emphasis on reform, opening, innovation, and high-quality development. It prioritized digital trade and emerging forms of service trade, promoted the deeper integration of digital technologies with industrial and value chains, advanced the servitization of manufacturing, and facilitated the agglomeration of producer services.

2.2. Theoretical Analysis

2.2.1. Direct Effects

The STIDPP is a comprehensive institutional arrangement encompassing institutional reform, greater openness, and innovation in development models. It can positively affect pollution reduction and carbon reduction through channels such as industrial structure upgrading, green technological innovation, environmental governance investment, and public environmental concern. First, the STIDPP facilitates industrial structure upgrading. The pilot policy prioritizes the development of knowledge-intensive service industries, including digital services, professional consulting, and service outsourcing. It encourages capital, labor, and technology to shift from energy-intensive and high-emission sectors to sectors characterized by high value added and low resource dependence. This reallocation reduces energy consumption and emission intensity per unit of output. Second, the STIDPP can promote green technological innovation. Greater openness of the service sector, especially to foreign investment, can broaden financing channels and support the development and diffusion of green technologies. The introduction of energy conservation, environmental protection, professional consulting, and related services facilitates the transfer of advanced technologies and managerial expertise to local firms. This process promotes the adoption and application of cleaner production technologies and pollution-control technologies. Third, the STIDPP may increase environmental governance investment. As pilot cities improve their level of openness and internationalization, local governments and firms face higher requirements for green development and environmental standards [21]. To improve the quality of service trade development and enhance urban green competitiveness, pilot regions may increase investment in environmental infrastructure, pollution-control projects,

and ecological protection. Finally, the STIDPP may enhance public environmental concern. The development of information services and environmental services helps improve the efficiency of environmental information dissemination and strengthen public awareness of green and low-carbon development. Increased public environmental concern can influence the behavior of firms and governments through green consumption and social supervision, thereby promoting pollution reduction and carbon reduction.

Based on the above analysis, the following hypotheses are proposed:

H1. *The STIDPP has a positive effect on pollution reduction and carbon reduction.*

H1a. *The STIDPP can promote pollution reduction and carbon reduction by facilitating industrial structure upgrading.*

H1b. *The STIDPP can promote pollution reduction and carbon reduction by fostering green technological innovation.*

H1c. *The STIDPP can promote pollution reduction and carbon reduction by increasing environmental governance investment.*

H1d. *The STIDPP can promote pollution reduction and carbon reduction by enhancing public environmental concern.*

2.2.2. Spatial Spillover Effects

The spatial spillover effects of the STIDPP on pollution reduction and carbon reduction may vary with geographic distance. For cities located close to pilot regions, the STIDPP may generate negative spatial spillover effects through resource siphoning and industrial relocation. Given resource constraints, STIDPP accelerates the agglomeration of factors such as capital, technology, and talent, leading to a high concentration of resources in pilot regions and intensifying resource competition in neighboring areas [20]. As a result, neighboring areas may face greater pressure for pollution reduction and carbon reduction due to insufficient investment in pollution control and constraints on green technological innovation. As discussed above, STIDPP accelerates industrial structure upgrading and strengthens environmental regulation in pilot regions, which may induce the relocation of some highly polluting and high-emission industries to neighboring areas [24], thereby increasing their burden of pollution reduction and carbon reduction. When regions are relatively distant from pilot regions, STIDPP may generate positive spatial spillover effects through technological innovation spillovers, the diffusion of public platforms, and policy demonstration. The effects of resource siphoning and industrial relocation are constrained by geographic distance and therefore have certain spatial boundaries. As geographic distance increases, the trickle-down effects of STIDPP gradually emerge. On the one hand, pilot construction promotes innovation in digital and green technologies, which can spill over to surrounding regions through the sharing of knowledge and experience. On the other hand, through policy demonstration, STIDPP encourages surrounding regions to draw on green development experience and adopt similar policy measures [25], such as providing interest-subsidy support for imported environmental services, thereby promoting local pollution reduction and carbon reduction. In addition, the Overall Plan for Deepening the Pilot Program for Innovative Development of Service Trade proposes the scientific construction and operation of national and regional public service platforms. Through these platforms, STIDPP supports the commercial application and diffusion of environmental services and expands their market demand across a wider area, thereby exerting a positive effect on pollution reduction and carbon reduction in surrounding regions.

Based on the above analysis, the following hypothesis is proposed:

H2. *The STIDPP generates spatial spillover effects on pollution reduction and carbon reduction, with these effects shifting from negative to positive as geographic distance increases.*

Based on the above theoretical analysis, the theoretical framework of this study is shown in Figure 1.

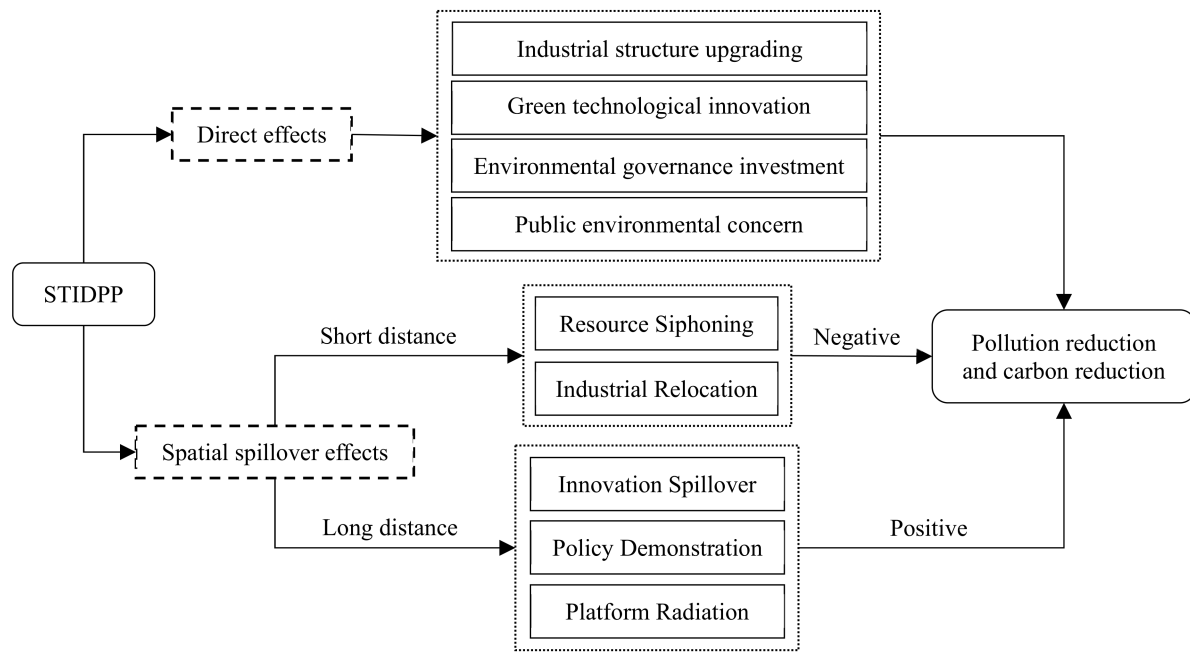


Figure 1. Theoretical framework.

3. Research Design

3.1. Models

3.1.1. Staggered DID Model

Considering that pilot designation is not completely random, pilot cities may already have had better economic foundations, service trade development conditions, or environmental governance capacity before policy implementation. To alleviate the potential policy endogeneity problem, this study uses the Staggered DID approach to compare the changes in pilot cities relative to non-pilot cities before and after policy implementation. City fixed effects are used to control for time-invariant city-specific characteristics, such as location conditions, industrial foundations, and institutional environments, while year fixed effects are used to control for common national-level time shocks, such as macroeconomic fluctuations and changes in environmental policies. Meanwhile, a series of control variables are included to mitigate the influence of economic, fiscal, and industrial factors on the estimation results. In the subsequent analysis, robustness checks, including the parallel trends test, placebo test, PSM-DID, and heterogeneous treatment effect test, are further conducted to verify the reliability of the results from the perspectives of trend comparability and sample comparability.

The specific form of the Staggered DID model is as follows:

$$Y_{it} = \alpha_0 + \alpha_1 ST_{it} + \alpha_2 CON_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (1)$$

where I denotes the city and t denotes the year. Y_{it} represents PRE, CRE, and PCE, respectively. ST_{it} is the policy dummy variable, indicating whether city I established a pilot

program in year t . CON_{it} denotes the control variables. M_i captures city fixed effects, γ_t captures year fixed effects, and ε_{it} is the random error term.

3.1.2. Spatial DID Model

To examine the spatial spillover effect of the STIDPP on pollution reduction and carbon reduction, the Spatial DID model is specified as follows:

$$Y_{it} = \alpha_0 + \rho_0 WY_{it} + \alpha_1 ST_{it} + \rho_1 WST_{it} + \alpha_2 CON_{it} + \rho_2 WCON_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (2)$$

where W denotes the spatial weight matrix; ρ_0 is the spatial autoregressive coefficient of the dependent variable; α_1 and ρ_1 are the coefficients of the local policy variable ST_{it} and its spatial lag WST_{it} , respectively; α_2 and ρ_2 are the coefficients of the local control variables and their spatial lags, respectively.

3.2. Variables

3.2.1. Dependent Variables

(1) Pollution-reduction efficiency (PRE) and carbon-reduction efficiency (CRE). From an input–output perspective, the Super-SBM model incorporating undesirable outputs is used to measure PRE and CRE [26]. The input factors are considered from three dimensions: capital, labor, and energy [27]. Capital input is represented by capital stock, labor input is measured by the number of employees in urban units at year-end, and energy input is measured by total energy consumption. Outputs include desirable and undesirable outputs. Desirable output is represented by real GDP. For undesirable outputs, the annual average concentration of $PM_{2.5}$ is used when measuring PRE, while carbon emissions are used when measuring CRE [28].

(2) The synergy between pollution reduction and carbon reduction (PCE). PRE and CRE are incorporated into the coupling coordination degree model to measure PCE [23,29]. The specific formulas are as follows:

$$C_{pc} = \frac{2\sqrt{U_p U_c}}{U_p + U_c} \quad (3)$$

$$T_{pc} = \alpha_p U_p + \alpha_c U_c \quad (4)$$

$$PCE = \sqrt{C_{pc} \times T_{pc}} \quad (5)$$

where C_{pc} denotes the coupling degree between PRE and CRE. U_p and U_c represent PRE and CRE after range standardization, respectively. T_{pc} denotes the comprehensive coordination index. α_p and α_c represent the weights of PRE and CRE, respectively, both of which are set at 50%. PCE denotes the coupling coordination degree between PRE and CRE.

3.2.2. Independent Variable

The independent variable is the policy dummy variable, ST. Specifically, if city I was designated as a pilot city under the STIDPP in year t , ST is assigned a value of 1 for city I in year t and all subsequent years, and 0 otherwise. Because some data are unavailable after 2022, the sample period ends in 2022. As a result, cities included in the third batch of the pilot program are observed for only two years within the study period. This limited number of observations is insufficient to fully capture the policy effect. Therefore, cities included in the first and second batches are defined as the treatment group [20,21]. As the early pilot regions of the STIDPP, the first and second batches of pilot cities can sufficiently reflect the policy effects during the implementation period and therefore have a certain degree of representativeness. However, considering that the first and second batches may

differ from the third batch in terms of service trade foundations and policy implementation capacity, this study further constructs an alternative policy dummy variable that includes all three batches of pilot regions in the robustness check section and re-estimates the model, so as to ensure that the core conclusions do not depend on the exclusion of the third batch of pilot cities.

3.2.3. Control Variables

The control variables include: (1) infrastructure construction (RAP), measured by road area per capita. Infrastructure construction may negatively affect pollution reduction and carbon reduction through the use of energy-intensive materials. (2) Social consumption level (CGS), measured by the logarithm of total retail sales of consumer goods. An increase in social consumption may stimulate demand for goods and services such as transportation, food processing, and durable consumer goods, thereby increasing greenhouse gas and pollutant emissions. (3) Science and technology expenditure (SE), measured by the logarithm of science and technology expenditure. Science and technology expenditure empowers pollution reduction and carbon reduction by promoting technological innovation. (4) Income level (IC), measured by the logarithm of the average wage of employees. Income level may affect energy consumption patterns and the ability to pay for environmental protection, thereby influencing pollution reduction and carbon reduction. (5) Financial development (FE), measured by the ratio of the year-end loan balance to the deposit balance of financial institutions. Financial development promotes pollution reduction and carbon reduction by easing financing constraints on environmental protection projects. (6) Education level (EDE), measured by the ratio of education expenditure to regional GDP. Improvements in education level help strengthen human capital accumulation and public environmental awareness, creating favorable conditions for pollution reduction and carbon reduction.

3.3. Data Sources and Descriptive Statistics

The research sample consists of panel data for 278 prefecture-level and above cities in China from 2011 to 2022 (hereafter referred to as cities). Hong Kong, Macao, Taiwan, and a small number of cities were excluded due to data unavailability. The data are mainly obtained from the China City Statistical Yearbook, China Industrial Statistical Yearbook, China Energy Statistical Yearbook, China Environmental Statistical Yearbook, and the CSMAR database. A small number of missing values are supplemented using linear interpolation. The descriptive statistics of the variables are reported in Table 1.

Table 1. Descriptive statistics.

Variables	N	Mean	SD	Min	Max
PRE	3336	0.5198	0.1699	0.1862	1.9772
CRE	3336	0.5121	0.1700	0.1480	1.9772
PCE	3336	0.4253	0.0965	0.0561	0.9984
ST	3336	0.0408	0.1978	0.0000	1.0000
RAP	3336	18.5526	7.7709	1.3700	60.0700
CGS	3336	15.6538	1.0699	5.4723	19.0129
SE	3336	10.5018	1.4484	6.6241	15.5293
IC	3336	10.9996	0.3676	8.5088	12.2922
FE	3336	0.7087	0.2301	0.0598	5.6132
EDE	3336	3.4524	1.7508	0.7534	14.8578

4. Empirical Analysis

4.1. Impacts of STIDPP on Pollution Reduction and Carbon Reduction

4.1.1. Baseline Regression Analysis

The baseline regression results are reported in Table 2. Columns (1)–(3) present the regression results without controlling for city and year fixed effects. Columns (4)–(6) report the results after controlling for city and year fixed effects, with standard errors clustered at the city level. Columns (7)–(9) further include control variables based on Columns (4)–(6). Under the two-way fixed effects specification with control variables included, the estimated coefficients of ST on PRE, CRE, and PCE are 0.1265, 0.1378, and 0.0796, respectively, all of which are significant at the 1% level. This indicates that, under given input-output conditions, the pilot policy significantly improves pollution-reduction efficiency, carbon-reduction efficiency, and the synergy between pollution reduction and carbon reduction. This finding is generally consistent with existing studies showing that environmental policies can improve green efficiency and environmental performance. In comparison, the STIDPP, as a non-direct environmental regulation policy, can also generate substantial green transformation effects. Based on these results, the STIDPP has a significant positive effect on pollution reduction and carbon reduction, and Hypothesis H1 is verified.

Table 2. Baseline regression results.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	PRE	CRE	PCE	PRE	CRE	PCE	PRE	CRE	PCE
ST	0.0668 *** (0.0148)	0.0598 *** (0.0149)	0.0293 *** (0.0084)	0.1254 *** (0.0268)	0.1368 *** (0.0268)	0.0796 *** (0.0157)	0.1265 *** (0.0264)	0.1378 *** (0.0266)	0.0796 *** (0.0156)
RAP							−0.0021 ** (0.0010)	−0.0019 ** (0.0009)	−0.0014 ** (0.0006)
CGS							−0.0379 *** (0.0138)	−0.0468 *** (0.0090)	−0.0253 *** (0.0067)
EDE							0.0181 ** (0.0071)	0.0110 (0.0067)	0.0078 ** (0.0039)
SE							−0.0024 (0.0065)	−0.0019 (0.0061)	−0.0011 (0.0037)
IC							0.0114 (0.0388)	−0.0074 (0.0387)	−0.0097 (0.0206)
FE							0.0063 (0.0288)	0.0163 (0.0325)	0.0100 (0.0162)
Constant	0.5170 *** (0.0030)	0.5096 *** (0.0030)	0.4241 *** (0.0017)	0.5147 *** (0.0011)	0.5065 *** (0.0011)	0.4220 *** (0.0006)	0.9789 ** (0.4913)	1.3264 *** (0.4560)	0.9284 *** (0.2538)
City FE	NO	NO	NO	YES	YES	YES	YES	YES	YES
Year FE	NO	NO	NO	YES	YES	YES	YES	YES	YES
N	3336	3336	3336	3336	3336	3336	3336	3336	3336
R ²	0.0060	0.0048	0.0036	0.6975	0.6934	0.7129	0.7081	0.7032	0.7243

Note: Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$.

4.1.2. Parallel Trend Test

The parallel trend assumption is tested using the event study approach, with the model specified as follows:

$$Y_{it} = \alpha_0 + \delta_k \sum_{k=-5}^5 ST_{it}^k + \alpha_2 CON_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (6)$$

where Y_{it} represents PRE, CRE, and PCE; ST_{it}^k denotes the policy dummy, with k indicating the k -th year since the implementation of STIDPP. The year prior to the policy implementation ($k = -1$) is set as the baseline. The coefficient δ_k captures the difference in PRE, CRE, and PCE between pilot and non-pilot cities in the k -th year relative to the baseline. The estimated values of δ_k and their 95% confidence intervals are presented in Figure 2. As shown in Figure 2, prior to the implementation of STIDPP, there are no significant differences in PRE, CRE, or PCE between the treatment and control groups, indicating that the parallel trend assumption is satisfied.

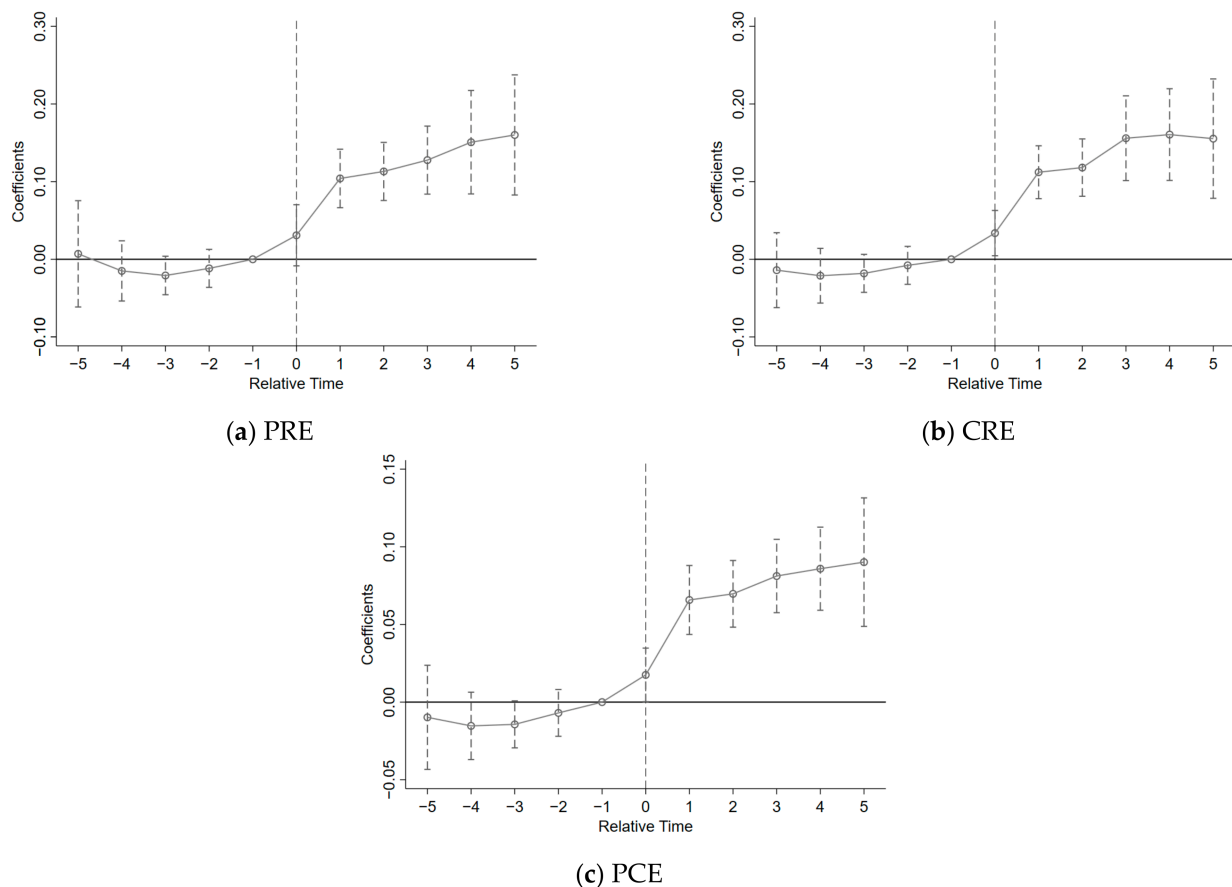


Figure 2. Parallel trend test.

4.1.3. Robustness Checks

(1) Placebo Test. The placebo test is conducted by randomly selecting a treatment group equal in size to the actual pilot group and randomly assigning the policy implementation timing. The original model is then re-estimated, and this procedure is repeated 1000 times to obtain the estimated coefficients of the pseudo-policy, along with their kernel densities and p -values (Figure 3). As shown in panels (a)–(c), the estimated coefficients of the pseudo-policy are symmetrically distributed around zero, and most p -values exceed 0.1. The actual estimated coefficients of ST are significantly different from the mean of the pseudo-policy coefficients. These results indicate that unobserved factors do not have a significant impact on the estimation outcomes.

(2) PSM-DID. To reduce the concern that the baseline estimates may be affected by non-random sample differences, this study re-estimates the policy effect using PSM-DID. Specifically, the control variables are first used to construct comparable treated and untreated samples through nearest-neighbor, radius, and kernel matching. The matched-sample regression results are presented in Table 3. The estimated effects of ST remain positive and significant under all three matching procedures, which further supports the robustness of the baseline conclusion.

(3) Heterogeneous treatment effect test. Since the pilot programs for the innovative development of service trade were established in multiple batches, the conventional Staggered DID may suffer from estimation bias caused by heterogeneous treatment effects. Therefore, the CSDID estimator is calculated to reduce potential bias [30]. The results show that, when PRE, CRE, and PCE are used as the dependent variables, the average treatment effects for the treatment group are 0.0858, 0.0749, and 0.0475, respectively, all of which are significant at the 1% level. In addition, a dynamic test is conducted using the SA

statistic [31] (Figure 4). The findings indicate that the baseline estimates remain robust after accounting for heterogeneous treatment effects.

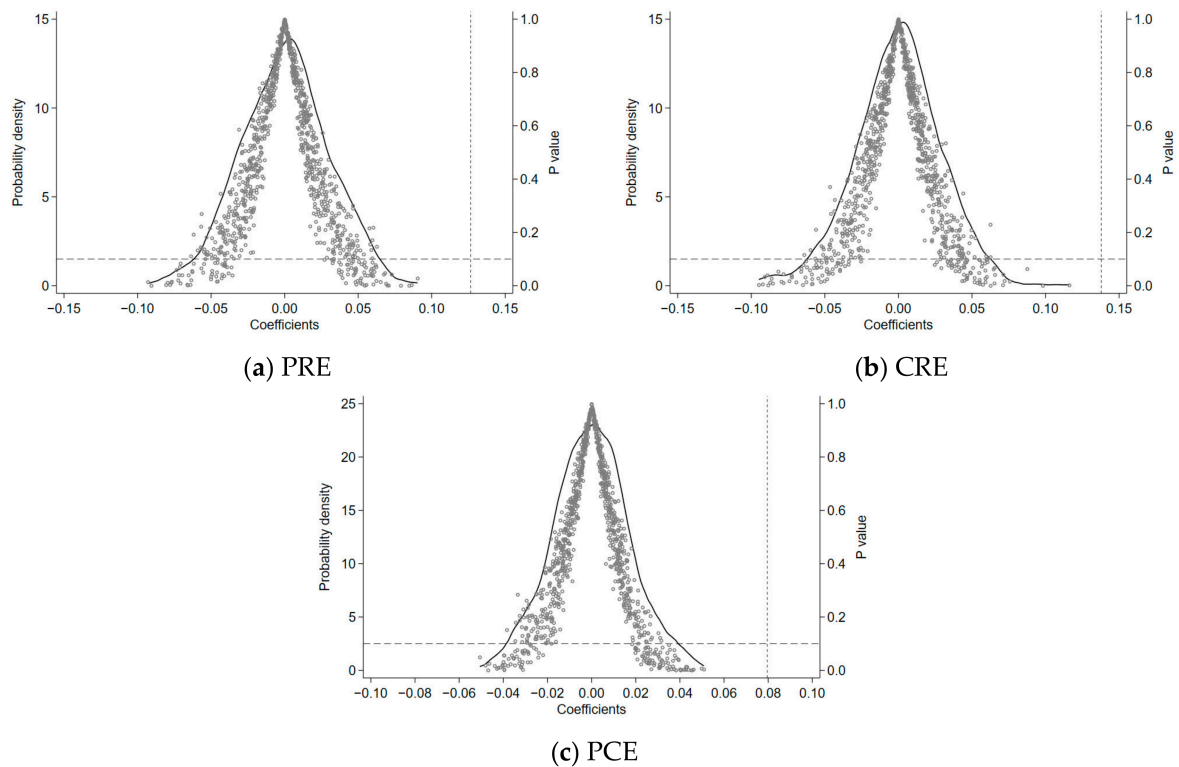


Figure 3. Placebo test.

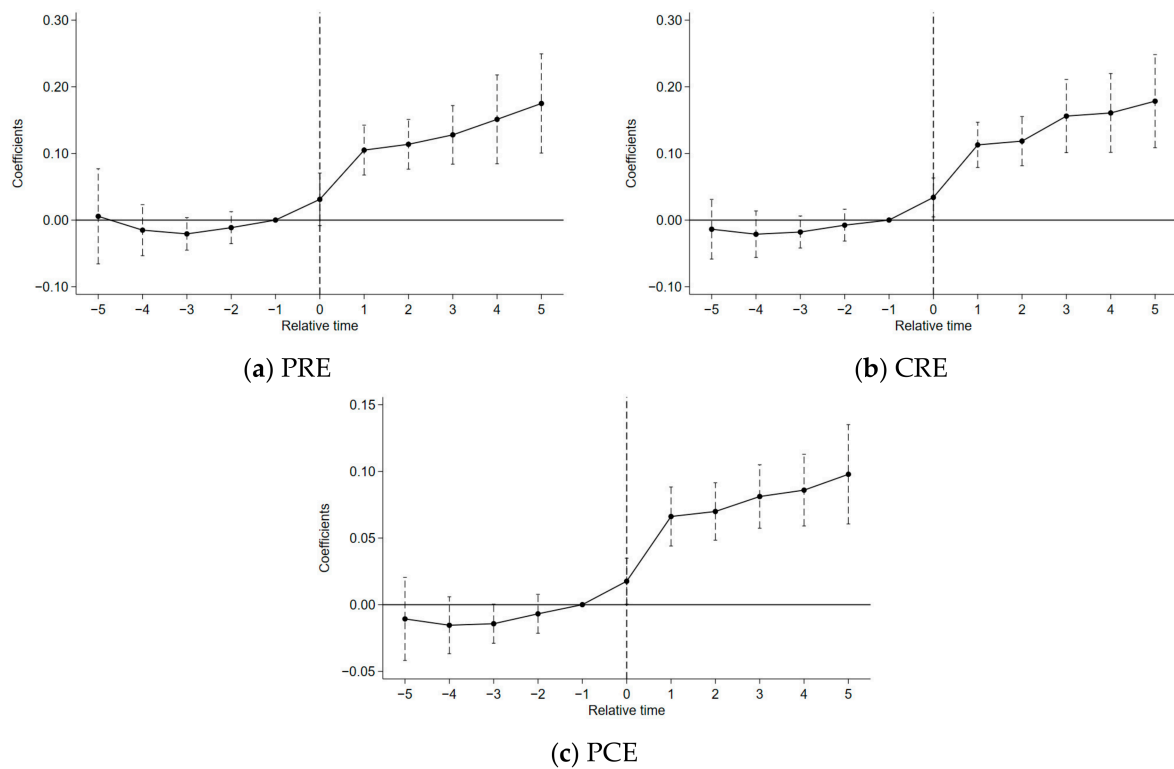


Figure 4. Heterogeneous treatment effect test.

Table 3. Regression results of PSM-DID.

Variables	Nearest-Neighbor Matching			Radius Matching			Kernel Matching		
	PRE	CRE	PCE	PRE	CRE	PCE	PRE	CRE	PCE
ST	0.0782 *** (0.0291)	0.0784 *** (0.0290)	0.0489 *** (0.0170)	0.0774 *** (0.0212)	0.0847 *** (0.0206)	0.0533 *** (0.0139)	0.0788 *** (0.0208)	0.0853 *** (0.0202)	0.0544 *** (0.0137)
Constant	−0.7635 (1.0799)	0.3499 (1.1844)	0.2392 (0.6308)	1.0454 ** (0.4914)	1.4018 *** (0.4524)	0.9638 *** (0.2533)	1.0459 ** (0.4906)	1.4048 *** (0.4515)	0.9640 *** (0.2529)
Control variables	YES	YES	YES	YES	YES	YES	YES	YES	YES
City FE	YES	YES	YES	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES	YES	YES	YES
N	698	698	698	3286	3286	3286	3289	3289	3289
R ²	0.8032	0.8237	0.8433	0.7038	0.6988	0.7210	0.7039	0.6992	0.7213

Note: Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$.

(4) Excluding interference from other policies. To exclude interference from other pilot policies, such as new energy demonstration cities (NED), intellectual property demonstration cities (IPD), national independent innovation demonstration zones (NID), and free trade zones (FTP), the corresponding policy dummy variables are constructed and included in the original model as controls. The regression results are reported in Table 4. After controlling for NED, IPD, NID, and FTP, respectively, the coefficients of ST for PRE, CRE, and PCE remain positive and significant, indicating that the baseline regression results are robust.

Table 4. Regression results excluding interference from other policies.

Variables	New Energy Demonstration Cities			Intellectual Property Demonstration Cities			National Independent Innovation Demonstration Zones			Free Trade Pilot Zones		
	PRE	CRE	PCE	PRE	CRE	PCE	PRE	CRE	PCE	PRE	CRE	PCE
ST	0.1274 *** (0.0263)	0.1387 *** (0.0265)	0.0803 *** (0.0154)	0.1139 *** (0.0236)	0.1229 *** (0.0232)	0.0705 *** (0.0132)	0.1051 *** (0.0261)	0.1159 *** (0.0264)	0.0661 *** (0.0154)	0.0980 *** (0.0249)	0.1047 *** (0.0253)	0.0618 *** (0.0149)
NED	0.0323 ** (0.0142)	0.0342 ** (0.0139)	0.0226 *** (0.0079)									
IPD				0.0705 *** (0.0141)	0.0835 *** (0.0164)	0.0514 *** (0.0087)						
NID							0.0778 *** (0.0153)	0.0796 *** (0.0146)	0.0490 *** (0.0088)			
FTP										0.0674 *** (0.0147)	0.0782 *** (0.0157)	0.0422 *** (0.0089)
Constant	0.9948 ** (0.4883)	1.3432 *** (0.4523)	0.9396 *** (0.2513)	0.9499 * (0.4927)	1.2920 *** (0.4573)	0.9073 *** (0.2542)	0.9376 * (0.4965)	1.2842 *** (0.4582)	0.9024 *** (0.2558)	1.0334 ** (0.4855)	1.3896 *** (0.4467)	0.9626 *** (0.2489)
Control variables	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
City FE	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
N	3336	3336	3336	3336	3336	3336	3336	3336	3336	3336	3336	3336
R ²	0.7093	0.7045	0.7261	0.7131	0.7102	0.7326	0.7153	0.7107	0.7332	0.7127	0.7094	0.7299

Note: Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

(5) Including the third batch of pilot regions. Since the third batch of pilot regions was established in 2020, its policy effects may not have been fully released within the sample period. Therefore, the baseline regression only considers the first two batches of pilot regions. To examine whether the treatment group setting affects the main conclusions, this study constructs an alternative policy dummy variable, STT, which includes all three batches of pilot regions, and substitutes it into the baseline model for re-estimation. The results are reported in Table 5. Under the three model specifications, namely without controlling for fixed effects, controlling for city and year fixed effects with standard errors clustered at the city level, and further adding control variables, the regression coefficients of STT on PRE, CRE, and PCE are all significantly positive. This indicates that, after including the third batch of pilot regions in the treatment group, the conclusion that the STIDPP promotes pollution reduction and carbon reduction still holds.

Table 5. Regression results after including the third batch of pilot regions.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	PRE	CRE	PCE	PRE	CRE	PCE	PRE	CRE	PCE
STT	0.0598 *** (0.0136)	0.0768 *** (0.0136)	0.0328 *** (0.0077)	0.1108 *** (0.0218)	0.1325 *** (0.0226)	0.0734 *** (0.0127)	0.1084 *** (0.0218)	0.1304 *** (0.0228)	0.0713 *** (0.0128)
RAP							−0.0019 * (0.0010)	−0.0016 * (0.0009)	−0.0013 ** (0.0006)
CGS							−0.0372 *** (0.0136)	−0.0460 *** (0.0087)	−0.0248 *** (0.0066)
EDE							0.0180 ** (0.0071)	0.0110 (0.0067)	0.0077 ** (0.0038)
SE							−0.0020 (0.0065)	−0.0018 (0.0060)	−0.0010 (0.0036)
IC							0.0107 (0.0387)	−0.0085 (0.0383)	−0.0102 (0.0205)
FE							0.0049 (0.0293)	0.0143 (0.0330)	0.0090 (0.0165)
Constant	0.5168 *** (0.0030)	0.5083 *** (0.0030)	0.4237 *** (0.0017)	0.5144 *** (0.0011)	0.5056 *** (0.0011)	0.4217 *** (0.0006)	0.9689 ** (0.4890)	1.3212 *** (0.4508)	0.9236 *** (0.2516)
City FE	NO	NO	NO	YES	YES	YES	YES	YES	YES
Year FE	NO	NO	NO	YES	YES	YES	YES	YES	YES
N	3336	3336	3336	3336	3336	3336	3336	3336	3336
R ²	0.0058	0.0095	0.0054	0.6978	0.6960	0.7143	0.7079	0.7051	0.7250

Note: Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

4.1.4. Heterogeneity Analysis

To examine the heterogeneous effects of the STIDPP on pollution reduction and carbon reduction across different types of cities, four grouping variables are defined based on economic development level, city size, industrial structure, and environmental regulation. Specifically, economic development level (PGDP) is defined using the median of per capita GDP as the threshold. Cities above the median are assigned a value of 1, and 0 otherwise. City size (SCA) is classified according to the Notice of the State Council on Adjusting the Criteria for City Size Classification. Using a resident population of 5 million as the threshold, cities are divided into large cities and small-to-medium cities, with large cities assigned a value of 1 and small-to-medium cities assigned a value of 0. Industrial structure (INS) is classified according to whether the value added of the tertiary industry exceeds that of the secondary industry, with service-oriented cities assigned a value of 1 and production-oriented cities assigned a value of 0. Environmental regulation (EFS) is measured by the share of environmental-protection-related word frequency in the total word frequency of the government work reports of prefecture-level cities. If the word frequency share is above the median, the variable is assigned a value of 1, and 0 otherwise. On this basis, interaction terms between ST and each grouping variable are constructed and incorporated into the following model for regression analysis:

$$Y_{it} = \alpha_0 + \varphi ST_{it} \cdot G_{it} + \alpha_1 ST_{it} + \omega G_{it} + \alpha_2 CON_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (7)$$

where G_{it} denotes the grouping variables, including PGDP, SCA, INS, and EFS; $ST_{it} \cdot G_{it}$ denotes the interaction term between ST and each grouping variable; the definitions of the remaining variables are the same as those in Model (1).

The regression results of the heterogeneity analysis are reported in Table 6.

Columns (1)–(3) present the heterogeneity results by economic development level. The regression coefficients of $ST \cdot PGDP$ on PRE, CRE, and PCE are all significantly positive, indicating that the promoting effect of the STIDPP on pollution reduction and carbon reduction is more pronounced in cities with higher levels of economic development. Cities with higher economic development levels usually have advantages in infrastructure and human capital, which enable them to effectively absorb the diffusion of technologies, knowledge, and managerial experience brought by service trade. Meanwhile, stronger

green innovation capacity among firms and stronger environmental governance capacity of governments help transform the advantages of service trade policies into pollution-control and low-carbon transformation performance.

Table 6. Regression results of heterogeneity analysis.

Variables	Economic Development Level			City Size			Industrial Structure			Environmental Regulation		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
	PRE	CRE	PCE	PRE	CRE	PCE	PRE	CRE	PCE	PRE	CRE	PCE
ST·PGDP	0.1226 *** (0.0449)	0.1188 *** (0.0438)	0.0721 ** (0.0298)									
ST·SCA				0.0852 * (0.0436)	0.1413 *** (0.0323)	0.0773 *** (0.0225)						
ST·INS							0.2037 *** (0.0256)	0.1712 *** (0.0267)	0.1265 *** (0.0150)			
ST·EFS										−0.0201 (0.0225)	−0.0442 ** (0.0180)	−0.0124 (0.0108)
PGDP	−0.0022 (0.0105)	0.0014 (0.0095)	−0.0001 (0.0059)									
SCA				0.0299 (0.0263)	0.0263 (0.0261)	0.0254 (0.0184)						
INS							−0.0128 (0.0090)	−0.0090 (0.0089)	−0.0077 (0.0052)			
EFS										−0.0112 ** (0.0055)	−0.0058 (0.0052)	−0.0047 (0.0029)
ST	0.0208 (0.0414)	0.0354 (0.0382)	0.0175 (0.0283)	0.0623 * (0.0318)	0.0317 * (0.0171)	0.0215 (0.0158)	−0.0697 *** (0.0121)	−0.0267 ** (0.0123)	−0.0421 *** (0.0073)	0.1359 *** (0.0309)	0.1616 *** (0.0296)	0.0858 *** (0.0160)
Constant	0.9851 ** (0.4962)	1.3432 *** (0.4612)	0.9356 *** (0.2569)	0.9746 ** (0.4905)	1.3264 *** (0.4543)	0.9251 *** (0.2522)	0.9903 ** (0.4915)	1.3393 *** (0.4586)	0.9359 *** (0.2540)	0.9736 ** (0.4942)	1.3315 *** (0.4573)	0.9271 *** (0.2550)
Control variables	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
City FE	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
N	3336	3336	3336	3336	3336	3336	3336	3336	3336	3336	3336	3336
R ²	0.7095	0.7045	0.7258	0.7093	0.7057	0.7273	0.7098	0.7043	0.7263	0.7091	0.7041	0.7250

Note: Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Columns (4)–(6) present the heterogeneity results by city size. The regression coefficients of ST·SCA on PRE, CRE, and PCE are all significantly positive, indicating that the promoting effect of the STIDPP on pollution reduction and carbon reduction is stronger in large cities. Large cities generally have larger markets and more concentrated producer services, which provide a market foundation and factor support for the STIDPP. Meanwhile, large cities are relatively more advanced in environmental facilities, platform construction, and public governance, making it easier for them to enhance policy effects through economies of scale and industrial agglomeration effects.

Columns (7)–(9) present the heterogeneity results by industrial structure. The regression coefficients of ST·INS on PRE, CRE, and PCE are 0.2037, 0.1712, and 0.1265, respectively, all of which pass the significance test at the 1% level. This indicates that the positive effect of the STIDPP on pollution reduction and carbon reduction is stronger in service-oriented cities. Service-oriented cities usually have a more developed service sector foundation and a higher-level institutional environment. They are also more compatible with policy contents such as digital services and environmental services. Therefore, they have stronger policy absorption capacity and can more effectively transform the openness dividends, innovation resources, and governance experience brought by the STIDPP into green development performance. By contrast, production-oriented cities are more dependent on energy consumption and may face higher green transformation costs in the short term, thereby weakening the environmental governance effect of the STIDPP.

Columns (10)–(12) present the heterogeneity results by environmental regulation. The regression coefficients of ST·EFS on PRE and PCE are negative but insignificant, while the coefficient on CRE is significantly negative at the 5% level. This indicates that, in regions with stronger environmental regulation, the marginal promoting effect of the STIDPP on CRE is weakened to some extent. One possible reason is that regions with stronger environmental regulation already had relatively high environmental governance levels and stricter low-carbon requirements before policy implementation, leaving relatively

limited room for marginal improvement in CRE. At the same time, stronger environmental regulation may also increase environmental compliance costs in the short term, forcing firms to allocate limited resources to meeting existing regulatory requirements. This may crowd out investment in servitization transformation and low-carbon innovation, thereby constraining the policy effect of the STIDPP to some extent.

4.1.5. Mechanism Analysis

According to the theoretical analysis above, industrial structure upgrading, green technological innovation, environmental governance investment, and public environmental concern are important channels through which the STIDPP promotes pollution reduction and carbon reduction. Based on this, the mechanism analysis model is specified as follows:

$$M_{it} = \beta_0 + \beta_1 ST_{it} + \beta_2 CON_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (8)$$

where M_{it} denotes the mechanism variables, including industrial structure upgrading (ISU), green technological innovation (GTI), environmental governance investment (EGI), and public environmental concern (EC). Industrial structure upgrading is measured by the ratio of the value added of the tertiary industry to that of the secondary industry. Green technological innovation is measured by the number of green invention patent applications per 10,000 people. Environmental governance investment is measured by the logarithm of investment in environmental pollution control. Public environmental concern is measured by the Baidu Search Index for “environmental pollution”. The definitions of the remaining variables are consistent with those in Equation (1).

The regression results of the mechanism analysis are reported in Table 7. The results in Columns (1) and (2) show that the STIDPP has a significantly positive effect on industrial structure upgrading. Upgrading the industrial structure toward low-resource-dependent and high-value-added sectors, such as the service sector, helps reduce energy consumption and pollution emission intensity. Therefore, the STIDPP can promote pollution reduction and carbon reduction by facilitating industrial structure upgrading, and Hypothesis H1a is supported. Columns (3) and (4) show that the regression coefficient of ST on GTI is significantly positive at the 1% level, indicating that the STIDPP can effectively foster green technological innovation. It may provide technical support for pollution reduction and carbon reduction in areas such as resource recycling and renewable energy development through channels such as financial support and technology introduction. Thus, Hypothesis H1b is supported. In Columns (5) and (6), the regression coefficient of ST on EGI is significantly positive, indicating that the STIDPP can increase environmental governance investment and provide financial support for environmental infrastructure construction and ecological environmental protection, thereby promoting pollution reduction and carbon reduction. Therefore, Hypothesis H1c is supported. In Columns (7) and (8), the regression coefficient of ST on EC is significantly positive at the 1% level, indicating that the STIDPP can enhance public environmental concern. Increased public environmental concern helps influence the behavior of firms and local governments through environmental participation and social supervision, thereby promoting pollution reduction and carbon reduction. Thus, Hypothesis H1d is supported.

4.2. Spatial Spillover Effects of STIDPP on Pollution Reduction and Carbon Reduction

4.2.1. Spatial Correlation Test

Spatial correlation is tested using Moran's I, with the formula specified as follows:

$$\text{Moran's } I = \frac{n \sum_{i=1}^n \sum_{j=1}^n W_{ij} (q_i - \bar{q})(q_j - \bar{q})}{\left(\sum_{i=1}^n \sum_{j=1}^n W_{ij} \right) \sum_{i=1}^n (q_i - \bar{q})^2} \quad (9)$$

where n denotes the total number of cities; q_i represents the attribute value of city i , and $\bar{q}$ is the mean of the attribute values across all cities; W_{ij} denotes the spatial weight matrix, where $W_{ij} = 1$ if city i and city j are adjacent, and $W_{ij} = 0$ otherwise.

Table 7. Regression results of the mechanism analysis.

Variables	Industrial Structure Upgrading		Green Technological Innovation		Environmental Governance Investment		Public Environmental Concern	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	ISU	ISU	GTI	GTI	EGI	EGI	EC	EC
ST	0.1759 ** (0.0736)	0.2027 *** (0.0740)	1.4602 *** (0.4454)	1.4054 *** (0.4486)	0.0727 ** (0.0282)	0.0844 *** (0.0294)	13.5029 *** (2.8364)	12.8657 *** (2.7613)
Constant	1.0704 *** (0.0030)	−0.3883 (0.9410)	0.6661 *** (0.0182)	12.9423 *** (4.7469)	3.2490 *** (0.0011)	3.9934 *** (0.7852)	22.7869 *** (0.1156)	−5.1049 (20.1975)
Control variables	NO	YES	NO	YES	NO	YES	NO	YES
City FE	YES	YES	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES	YES	YES
N	3336	3336	3336	3336	3336	3336	3336	3336
R ²	0.8691	0.8821	0.6585	0.6640	0.9127	0.9131	0.9458	0.9466

Note: Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$.

As reported in Table 8, the Moran's I indices of PRE, CRE, and PCE are all positive and statistically significant across the sample period, indicating that PRE, CRE, and PCE all exhibit positive spatial correlation. The Moran's I values for all three measures follow a pattern of first declining and then rising, suggesting that their positive spatial correlation initially weakens and subsequently strengthens. A comparison between the Moran's I values of PRE and CRE further shows that the positive spatial correlation of PRE is slightly stronger than that of CRE.

Table 8. Moran's I indices of PRE, CRE, and PCE.

Year	PRE		CRE		PCE	
	Moran's I	p-Value	Moran's I	p-Value	Moran's I	p-Value
2011	0.1973	0.0000	0.1678	0.0000	0.1565	0.0001
2012	0.2121	0.0000	0.2371	0.0000	0.1890	0.0000
2013	0.1992	0.0000	0.1602	0.0001	0.1507	0.0002
2014	0.1173	0.0038	0.1023	0.0111	0.0753	0.0590
2015	0.1300	0.0014	0.0911	0.0232	0.0825	0.0392
2016	0.1157	0.0043	0.1320	0.0012	0.1075	0.0079
2017	0.2498	0.0000	0.2283	0.0000	0.2263	0.0000
2018	0.2383	0.0000	0.2152	0.0000	0.2090	0.0000
2019	0.2556	0.0000	0.1950	0.0000	0.2099	0.0000
2020	0.2793	0.0000	0.1438	0.0004	0.1867	0.0000
2021	0.2688	0.0000	0.1965	0.0000	0.1958	0.0000
2022	0.2401	0.0000	0.2781	0.0000	0.2209	0.0000

To further analyze local spatial correlation, we calculate the Local Moran's I of PRE, CRE, and PCE, and construct Moran scatter plots. The specific formulas are as follows:

$$I_i = \frac{\varphi_i}{s^2} \sum_{j=1}^n W_{ij} \varphi_j \quad (10)$$

$$\varphi_i = (X_i - \bar{X}_i), \varphi_j = (X_j - \bar{X}_j) \quad (11)$$

where φ_i denotes the deviation of sample X_i from the mean, and φ_j denotes the deviation of sample X_j from the mean; W_{ij} denotes the spatial weight matrix, which is defined in the same way as in Equation (9).

The Moran scatter plots for PRE, CRE, and PCE are presented in Figure 5. Most cities are concentrated in Quadrants I and III, indicating that the spatial distributions of PRE, CRE, and PCE exhibit “high-high” and “low-low” clustering patterns. Panels (a)–(d) show that a relatively large number of cities are located in Quadrant III, suggesting that PRE and CRE tend to display low–low clustering. Panels (e)–(f) show that cities gradually shift from a relatively dispersed distribution towards Quadrants I and III, indicating that the positive spatial agglomeration of PCE progressively strengthens.

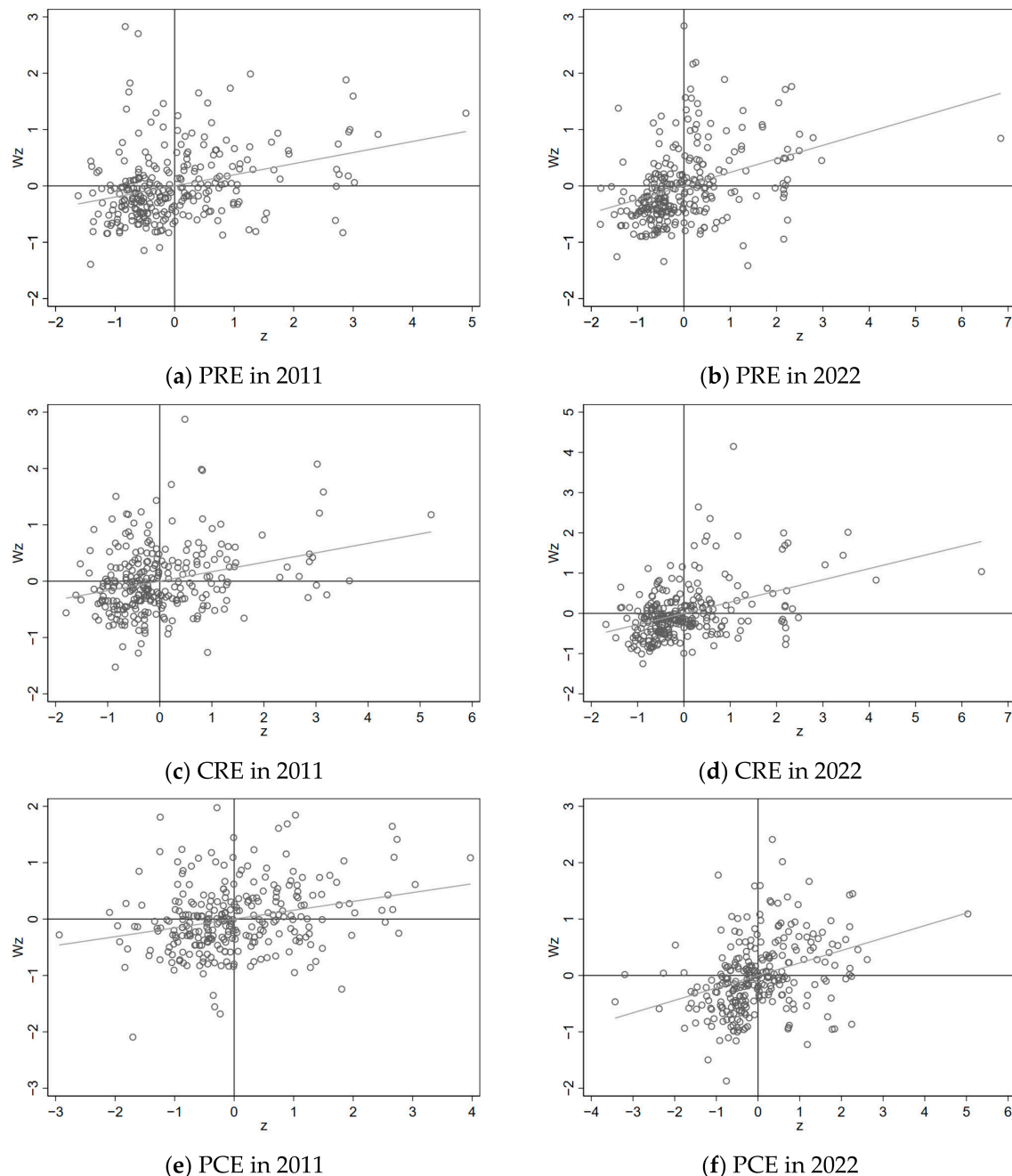


Figure 5. Moran scatter plots for PRE, CRE, and PCE.

4.2.2. Spatial DID Analysis

The regression results of the spatial DID model based on the contiguity matrix, the geographic distance matrix, and the economic–geographic matrix are reported in Table 9. The main regression coefficients of ST on PRE, CRE, and PCE are all positive and significant,

consistent with the baseline results. The spatial autoregressive coefficients of PRE, CRE, and PCE are all positive and significant, indicating that there is a positive spatial correlation in pollution reduction and carbon reduction among cities. Adjacent cities tend to share similar natural resource endowments and geographic conditions, giving rise to environmental interdependence. Local environmental improvement can benefit neighboring areas, while the aggravation of local pollution can be transmitted to surrounding areas through pathways such as the atmosphere and water flow.

Table 9. Spatial DID regression results.

Variables	Contiguity Matrix			Geographic Distance Matrix			Economic–Geographic Matrix		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	PRE	CRE	PCE	PRE	CRE	PCE	PRE	CRE	PCE
ST	0.1294 *** (0.0128)	0.1488 *** (0.0130)	0.0864 *** (0.0071)	0.1211 *** (0.0123)	0.1362 *** (0.0125)	0.0786 *** (0.0068)	0.1261 *** (0.0125)	0.1432 *** (0.0127)	0.0830 *** (0.0069)
WST	−0.0362 * (0.0216)	−0.0755 *** (0.0219)	−0.0442 *** (0.0120)	−0.5134 ** (0.2314)	−0.7110 *** (0.2358)	−0.4906 *** (0.1282)	−0.1249 *** (0.0429)	−0.1479 *** (0.0437)	−0.0977 *** (0.0237)
Spatial rho	0.1761 *** (0.0219)	0.1306 *** (0.0221)	0.1357 *** (0.0229)	0.6277 *** (0.0887)	0.5795 *** (0.0985)	0.5670 *** (0.0993)	0.3171 *** (0.0455)	0.3000 *** (0.0466)	0.3000 *** (0.0476)
Variance sigma _{2_e}	0.0081 *** (0.0002)	0.0084 *** (0.0002)	0.0025 *** (0.0001)	0.0080 *** (0.0002)	0.0083 *** (0.0002)	0.0025 *** (0.0001)	0.0082 *** (0.0002)	0.0084 *** (0.0002)	0.0025 *** (0.0001)
Control variables	YES	YES	YES	YES	YES	YES	YES	YES	YES
City FE	YES	YES	YES	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES	YES	YES	YES
N	3336	3336	3336	3336	3336	3336	3336	3336	3336
R ²	0.0291	0.0001	0.0034	0.0187	0.0008	0.0016	0.0093	0.0001	0.0002

Note: Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

To further clarify the spatial spillover effects of STIDPP on pollution reduction and carbon reduction, the total effect is decomposed into direct and indirect effects. The direct effect refers to the impact of STIDPP within a city, whereas the indirect effect captures the spatial spillover effect of STIDPP on pollution reduction and carbon reduction. As reported in Table 10, the direct effects of STIDPP on PRE, CRE, and PCE are all positive and significant, indicating that the policy effectively promotes pollution reduction and carbon reduction within cities. By contrast, the indirect effects of STIDPP are negative, suggesting that the pilot policy may generate negative spillover effects on neighboring cities by attracting resources to pilot areas and inducing the relocation of some high-pollution and high-energy-consuming industries and projects. Compared with CRE, the indirect effect of STIDPP on PRE is less statistically significant, possibly because pollution control is more amenable to end-of-pipe treatment and tends to yield short-term results more readily than carbon reduction. Moreover, local governments usually respond more quickly to environmental pollution, which may partially mitigate the negative effect of STIDPP on PRE in surrounding areas.

Table 10. Results of effect decomposition.

Variables	Contiguity Matrix			Geographic Distance Matrix			Economic–Geographic Matrix		
	PRE	CRE	PCE	PRE	CRE	PCE	PRE	CRE	PCE
direct effect	0.1292 *** (0.0130)	0.1474 *** (0.0132)	0.0856 *** (0.0072)	0.1174 *** (0.0129)	0.1315 *** (0.0131)	0.0753 *** (0.0072)	0.1249 *** (0.0129)	0.1418 *** (0.0130)	0.0819 *** (0.0071)
indirect effect	−0.0167 (0.0233)	−0.0637 *** (0.0228)	−0.0370 *** (0.0125)	−1.2652 * (0.6978)	−1.6043 ** (0.6871)	−1.0960 *** (0.3972)	−0.1254 ** (0.0585)	−0.1509 *** (0.0581)	−0.1043 *** (0.0317)
total effect	0.1125 *** (0.0249)	0.0837 *** (0.0240)	0.0486 *** (0.0132)	−1.1479 (0.7005)	−1.4728 ** (0.6897)	−1.0207 ** (0.3988)	−0.0006 (0.0605)	−0.0091 (0.0600)	−0.0224 (0.0328)

Note: Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

4.2.3. Characteristics and Boundaries of Spatial Spillover Effects

To further examine the heterogeneity of spatial spillover effects across different geographic distances and to identify their attenuation boundaries, spatial weight matrices based on different geographic distance thresholds are constructed as follows:

$$W_{ij}^d = \begin{cases} \frac{1}{d_{ij}}, & d_{ij} \geq d \\ 0, & d_{ij} < d \end{cases} \quad (12)$$

where d_{ij} denotes the geographic distance between city i and city j , and d represents the distance threshold. The threshold starts at 100 km and increases by 50 km each time. Since variables beyond 700 km may be more affected by interprovincial boundaries and spatial spillover effects may be more susceptible to outliers, the maximum threshold is set at 700 km.

By incorporating the W_{ij}^d matrix into the Spatial DID model, the indirect effects (spatial spillover effects) of ST on PRE, CRE, and PCE under different geographic distance thresholds are estimated, with the corresponding coefficients and significance levels reported in Figure 6. Specifically, when the geographic distance is within 200 km, the spatial spillover effects of the STIDPP are mainly negative. The STIDPP improves the institutional openness and service-sector agglomeration capacity of pilot cities, which may strengthen their short-term siphoning effect on capital, talent, technology, and other factors from neighboring cities, thereby weakening the resource allocation and green transformation capacity of surrounding regions. Meanwhile, in the process of promoting industrial structure upgrading and environmental governance in pilot cities, some energy-intensive and high-emission activities may be transferred to nearby areas, thus generating negative spatial spillover effects over short distances. As geographic distance gradually increases, the negative spatial spillover effects weaken. When the geographic distance exceeds 300 km, the spatial spillover effects shift from negative to positive, reach a peak at around 450 km, and then decline slowly. This suggests that, within a medium-distance range, the positive externalities of the STIDPP may gradually outweigh the negative effects caused by resource competition and industrial relocation. On the one hand, the green technologies and professional service capacity formed in pilot cities may diffuse to other cities through firm cooperation, industrial-chain linkages, and service trade platforms. On the other hand, the institutional innovation experience and green development practices accumulated through the pilot policy may be absorbed by other regions through demonstration and learning effects. Medium-distance cities maintain certain economic linkages with pilot cities but are not fully exposed to direct resource competition, making them more likely to obtain positive spillovers through technology diffusion and policy learning. When the distance further increases to 550 km or above, the spatial spillover effects gradually weaken and become statistically insignificant. One possible reason is that economic linkages and industrial connections between cities gradually decline as geographic distance increases, while information costs and coordination costs also rise accordingly. These factors may limit technology diffusion, service sharing, and policy learning effects. Based on these results, the spatial spillover effects of the STIDPP on pollution reduction and carbon reduction show a trend of shifting from negative to positive and then becoming statistically insignificant as geographic distance increases. Therefore, Hypothesis H2 is verified.

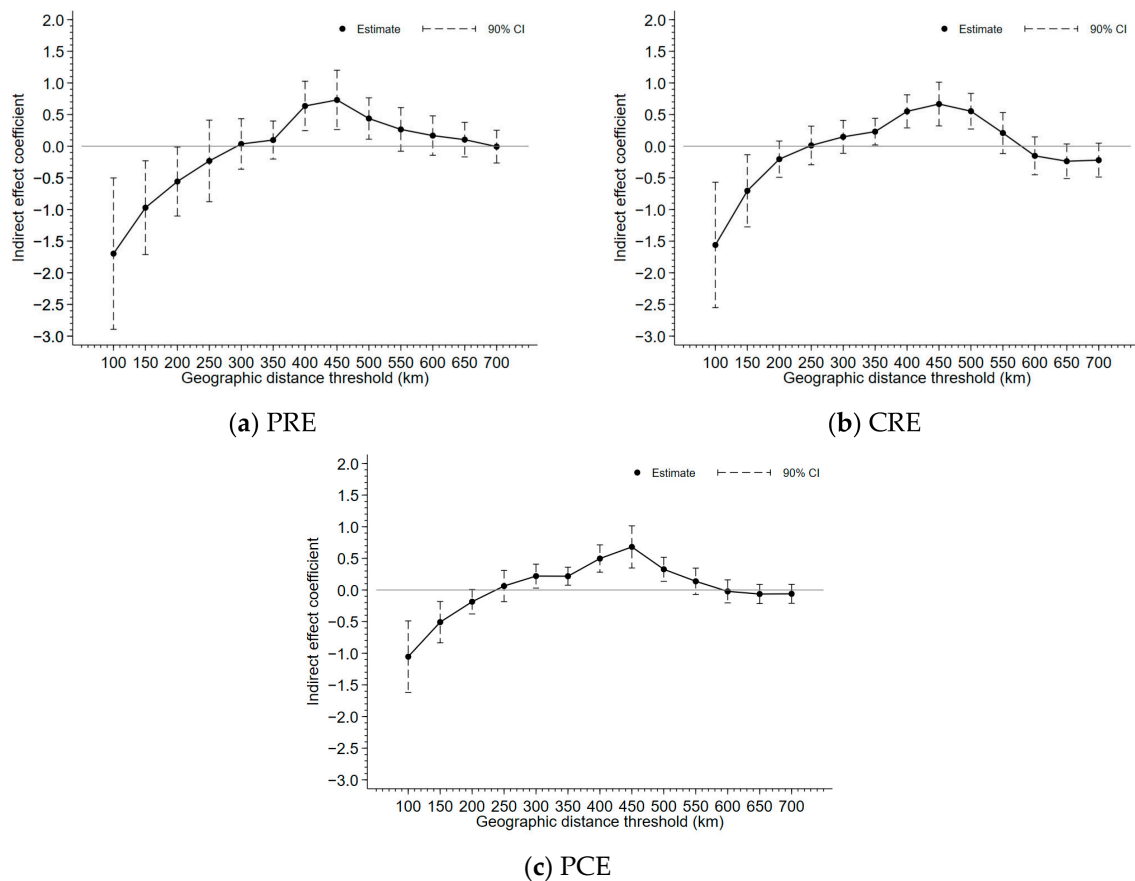


Figure 6. Spatial spillover effects based on different geographic distance thresholds.

5. Discussion

The results show that the STIDPP not only promotes pollution reduction and carbon reduction, but also helps improve the synergy between the two. This finding is generally consistent with existing studies showing that service trade and service-sector openness can improve environmental performance. It also echoes recent research suggesting that low-carbon policies may generate climate co-benefits beyond carbon reduction [32]. The contribution of this study lies in two aspects. On the one hand, instead of examining a single pollution or carbon emission indicator, this study evaluates policy effects from three dimensions: pollution-reduction efficiency, carbon-reduction efficiency, and the synergy between pollution reduction and carbon reduction. On the other hand, it further identifies the spatial spillover characteristics and distance boundaries of the environmental effects of the STIDPP, providing empirical evidence for understanding the regional environmental externalities of service trade policies.

The mechanism analysis shows that the environmental effects of the STIDPP are not only derived from the expansion of service trade scale, but are also jointly associated with industrial structure upgrading, green technological innovation, environmental governance investment, and public environmental concern. Industrial structure upgrading helps reduce cities' dependence on energy-intensive and high-emission industries. Green technological innovation enhances clean production and pollution-control capacity. Environmental governance investment strengthens the local foundation for environmental governance. Public environmental concern promotes improvements in the environmental behavior of firms and governments through social supervision and green consumption. Therefore, the STIDPP is not only an openness and innovation policy in the field of service trade, but also has an institutional effect in promoting urban green and low-carbon transformation.

The heterogeneity analysis shows that the policy effects of the STIDPP are jointly influenced by cities' development foundations, industrial structure characteristics, and environmental governance conditions. Regions with higher levels of economic development and larger city size usually have stronger innovation capacity, governance capacity, and factor agglomeration capacity, making it easier for them to transform the advantages of service trade policies into green development performance. Service-oriented cities have stronger policy absorption and transformation capacity because their industrial structures are more compatible with digital services and environmental services. The heterogeneity results for environmental regulation show that stronger environmental regulation does not further strengthen the overall policy effect of the STIDPP. In particular, in terms of CRE, its promoting effect is relatively weaker in regions with stronger environmental regulation. One possible reason is that regions with stronger environmental regulation already have a better environmental governance foundation, leaving limited room for the STIDPP to further improve CRE.

The spatial spillover analysis shows that the environmental effects of the STIDPP exhibit clear distance-dependent characteristics. The pilot policy significantly improves local pollution reduction and carbon reduction performance, but generates negative spillover effects on surrounding cities within a relatively short distance. This may be related to resource siphoning, factor competition, or the relocation of energy-intensive activities. As distance increases, factors such as green technology diffusion, policy demonstration, and the sharing of service trade platforms may gradually lead to the emergence of positive spillover effects. When the distance further expands, intercity linkages weaken, and the spatial spillover effects become statistically insignificant. This study mainly reveals the spatial boundaries and distance-dependent characteristics of the environmental effects of the STIDPP. The explanations of specific spatial transmission mechanisms are mainly reasonable inferences based on theoretical logic and empirical evidence, and do not constitute direct mechanism tests.

6. Research Conclusions and Recommendations

Using panel data for 278 Chinese cities from 2011 to 2022, this study systematically examines the effects of the STIDPP on pollution reduction and carbon reduction, as well as its spatial spillover effects, by employing the Staggered DID and Spatial DID models. The results indicate that the STIDPP significantly improves PRE, CRE, and PCE. This finding remains robust after a series of tests, including a placebo test, PSM-DID estimation, a heterogeneous treatment effect test, and controls for interference from other policies. The mechanism analysis shows that industrial structure upgrading, green technological innovation, environmental governance investment, and public environmental concern are important channels through which the STIDPP promotes pollution reduction and carbon reduction. Further analysis reveals substantial heterogeneity in the effects of the STIDPP across cities. Its positive effects on pollution reduction and carbon reduction are more pronounced in cities with higher levels of economic development, larger urban populations, and service-oriented industrial structures. Meanwhile, in regions with stronger environmental regulation, the promoting effect of the STIDPP on CRE is relatively weaker. The spatial analysis shows that the STIDPP generates significant spatial spillover effects on pollution reduction and carbon reduction, and these effects shift from negative to positive and then become statistically insignificant as geographic distance increases. This indicates that the spatial impacts of the STIDPP have clear distance boundaries and stage-specific differences.

Based on the above findings, several policy implications can be proposed. First, a policy coordination mechanism between service trade and environmental protection should

be established, and green development goals should be embedded in the selection of pilot projects and performance evaluation. Specifically, a cross-departmental coordination mechanism can be established to include green service trade, energy management, environmental consulting, green certification, and related services in the list of key supported areas. In the evaluation of pilot policies, indicators related to the supply of green technology services and environmental governance performance should be added. Second, service trade support tools for firms' green transformation should be developed. Pilot regions can explore the establishment of a green and low-carbon service subsidy mechanism to support firms in purchasing professional services such as energy-saving diagnosis, environmental monitoring, and green technology consulting. For cities with weaker economic foundations and relatively lagging service-sector development, priority should be given to strengthening digital infrastructure and public service platforms, so as to enhance their capacity to capture the policy dividends of the STIDPP. For regions with stronger environmental regulation, measures such as subsidies for green technological upgrading can be adopted to reduce the cost for firms to shift from passive compliance to proactive innovation. Finally, a cross-regional green service trade coordination mechanism should be established. Specifically, pilot cities and surrounding cities can jointly establish a coordinated assessment system for the transfer of energy-intensive and high-emission projects, so as to prevent the STIDPP from transferring environmental governance pressure to surrounding regions through resource siphoning and industrial adjustment. Meanwhile, pilot cities and surrounding regions should be encouraged to jointly build green service trade public platforms, promote information sharing on environmental monitoring data, green technologies, and environmental service institutions, and strengthen the positive spillover effects of the STIDPP in terms of technology diffusion and service sharing. For surrounding regions facing environmental pressure, green development funds and cross-regional green project co-construction mechanisms can be explored to guide pilot cities and surrounding cities toward a regional green development pattern characterized by shared benefits and shared responsibilities.

Although this study systematically analyzes the effects of the STIDPP on pollution reduction and carbon reduction from a multi-dimensional perspective, there are still certain limitations. First, the study is based on city-level data and cannot fully depict the behavioral responses at the micro levels such as enterprises and residents. Second, the construction of PRE and CRE relies on efficiency index measurement, which may have certain measurement errors. Meanwhile, PM_{2.5} concentration and carbon emissions differ in their physical meanings, formation mechanisms, and policy responses. Therefore, the interpretation of the synergy between pollution reduction and carbon reduction should be treated with caution. Third, although this study adopts multiple robustness checks to mitigate endogeneity concerns, it is still difficult to completely rule out the influence of time-varying unobservable factors. Fourth, the spatial weight matrix cannot fully capture actual factor flows and policy diffusion paths. Therefore, the interpretation of spatial spillover effects is mainly based on reasonable inference, and their underlying mechanisms require further examination. Finally, this study is based on a sample of Chinese cities, and the policy background of the STIDPP has certain specific characteristics. Therefore, caution is needed when extending the conclusions to other countries or institutional contexts. Future research could combine firm-level data, industrial relocation data, and innovation cooperation networks to further examine the environmental effects and spatial spillover effects of the STIDPP from the perspectives of micro-level mechanisms and dynamic evolution, and conduct comparative studies across different countries and institutional contexts.

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