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URBAN INNOVATION AGGLOMERATION AND THE SYNERGISTIC EFFECTS OF POLLUTION AND CARBON REDUCTION

HongTao Li*, ChenWei Zhang
School of Politics and Public Administration, Guangxi Minzu University, Nanning 530006, Guangxi, China.
**Corresponding Author: HongTao Li*

Abstract: Urban innovation agglomeration plays an important role in promoting regional green transformation and achieving the synergistic governance of pollution reduction and carbon emission reduction. From the perspective of agglomeration economics, this paper investigates how urban innovation agglomeration enhances the synergistic efficiency of pollution and carbon reduction through three channels: source prevention, process control, and end-of-pipe interception. The results show that: there is a significant inverted U-shaped nonlinear relationship between urban innovation agglomeration and the synergistic efficiency of pollution and carbon reduction. This study verifies the nonlinear relationship between urban innovation agglomeration and the synergistic efficiency of pollution and carbon reduction, providing empirical evidence for identifying the appropriate range of innovation factor agglomeration and formulating regional green synergy policies.
Keywords: Urban agglomeration; Innovation agglomeration; Technological innovation; Pollution and carbon reduction; Synergistic efficiency

1 INTRODUCTION

Against the backdrop of global climate change and ecological environmental crises, the coordinated reduction of pollution and carbon emissions has become an important strategic pathway for China to advance ecological civilization. The essence of synergistic pollution and carbon reduction lies in promoting the realization of pollution control and carbon mitigation targets through systemic governance transformation, supported by appropriate policies and institutional mechanisms, thereby maximizing environmental, climate, and economic benefits. Coordinated pollution and carbon reduction can help overcome the limitations of fragmented governance models and promote high-quality development. Therefore, exploring ways to enhance the synergy between pollution reduction and carbon reduction is of great practical significance for promoting economic and social development and achieving the goal of building a "Beautiful China."
However, current practices of pollution and carbon reduction still face considerable uncertainties and challenges. In particular, both pollution reduction and carbon mitigation are jointly affected by multiple factors, including technological innovation, industrial structure, and energy structure. The coordination between pollution reduction and carbon reduction cannot be achieved by relying on a single subsystem alone; rather, it requires the mutual embedding and joint functioning of multiple subsystems, including the economy, technology, and energy[1].

1.1 Research Background and Significance

Against this background, urban innovation agglomeration, as a new form of spatial and organizational arrangement, brings together innovation factors such as knowledge, technology, talent, and capital. Through knowledge spillovers, economies of scale, and network-based collaboration, it systematically facilitates the diffusion of technologies from research and development to industrial application. Theoretically, however, the relationship between urban innovation agglomeration and the synergistic efficiency of pollution and carbon reduction remains contested. Some scholars argue that urban innovation agglomeration can promote both pollution reduction and carbon mitigation by improving energy use efficiency[2], optimizing the energy structure and facilitating industrial upgrading [3-4], thereby exerting a positive effect on synergistic efficiency. Other scholars hold the opposite view, arguing that technological innovation may be accompanied by a "rebound effect"[5]. Moreover, some studies suggest that the relationship between urban technological innovation and the synergistic efficiency of pollution and carbon reduction may exhibit a more complex nonlinear pattern. For example, as proposed by the Environmental Kuznets Curve (EKC) hypothesis, economic development and environmental pollution may follow an inverted U-shaped relationship across different stages of development, initially intensifying environmental pressure before eventually contributing to its reduction[6].

1.2 Research Questions and Objectives

Therefore, as an innovative organizational form, does urban innovation agglomeration have a linear or nonlinear relationship with the synergistic efficiency of pollution and carbon reduction? More importantly, how is such synergy achieved? To answer these questions, this study takes Chinese cities at the prefecture level and above as the research sample and empirically examines the impact of urban innovation agglomeration on the synergistic efficiency of pollution and carbon reduction. This study has both theoretical and practical value.

2 THEORETICAL FOUNDATION AND RESEARCH HYPOTHESES

Urban innovation agglomeration refers to the spatial concentration of innovation factors, such as R&D talent, research institutions, high-tech enterprises, and venture capital, in a limited number of specific cities. Innovation-driven development theory suggests that, with the development of new-generation information technology industries, innovation factors such as R&D personnel, research institutions, high-tech industries, and venture capital become further concentrated, thereby promoting local technological progress and generating a technological effect[7]. On the one hand, this technological effect promotes the R&D and application of green production technologies, energy-saving and consumption-reduction technologies, and environmental governance technologies. It improves firms' efficiency in the use of resources and energy, facilitates the substitution of clean energy for traditional polluting energy sources, reshapes the energy structure, and promotes the low-carbon transformation of the energy mix. At the same time, it contributes to the green upgrading of industrial production modes, thereby reducing the intensity of pollutant and carbon emissions at the source and promoting the synergy between pollution reduction and carbon mitigation.

On the other hand, as the degree of innovation agglomeration continues to increase, the concentration of innovation factors may exceed a reasonable threshold, giving rise to factor congestion. The supply of R&D talent, capital, and other resources may become increasingly constrained, which raises the cost of green innovation in the market. Meanwhile, excessive agglomeration may intensify urban energy demand and production-related emissions, thereby weakening the emission-reduction effect of technological progress. In this case, innovation agglomeration may instead constrain and impede the synergistic efficiency of pollution and carbon reduction. Since innovation agglomeration may exert both a positive driving effect and a negative inhibiting effect on the synergy between pollution reduction and carbon mitigation, and since these effects change dynamically with the development level of innovation agglomeration, the relationship between urban innovation agglomeration and the synergistic efficiency of pollution and carbon reduction is unlikely to be simply linear; rather, it may exhibit a nonlinear pattern.

Based on the above analysis, this study further examines the relationship between urban innovation agglomeration and the synergistic efficiency of pollution and carbon reduction. At the initial stage of urban innovation agglomeration, the scale of agglomeration is relatively limited, and innovation resources are concentrated in particular cities, while resource allocation has not yet reached an optimal state. This may increase the cost of environmental pollution control and generate a negative shock to environmental governance. At this early stage, economic activities continue to concentrate, and the effect of economic expansion outweighs the emission-reduction effect of technological progress. The increase in emissions caused by economic expansion far exceeds the reduction effect brought about by technological progress. As output expands, the total amount of pollution emissions within a given spatial unit increases, resulting in a rise rather than a decline in total pollutant and carbon emissions, and thus giving rise to agglomeration diseconomies[8].

Meanwhile, innovation resources remain limited at this stage. Due to the high investment requirements, long payback periods, and strong externalities associated with green technology R&D, green innovation is often difficult to become the preferred choice of the market. In pursuit of short-term and high returns, firms may allocate innovation resources to non-green sectors such as traditional manufacturing, which may crowd out green innovation enterprises. In addition, affected by rising factor costs, local green and environmental protection industries may be forced to relocate to surrounding areas with lower costs, while the remaining highly polluting industries may lead to a reverse adjustment of the local industrial structure. Taken together, in the early stage of development, urban innovation agglomeration tends to exert an overall inhibiting effect on the synergistic efficiency of pollution and carbon reduction.

However, as the level of urban innovation agglomeration continues to rise and exceeds a certain threshold, energy use efficiency gradually improves, the above negative effects weaken, and innovation agglomeration begins to generate a positive driving effect on environmental governance. Once innovation factors form large-scale agglomeration, the spatial proximity of a large number of firms promotes the exchange of knowledge, experience, and professional skills among workers[9], which helps improve overall labor productivity in the market. Close interaction among firms within agglomeration areas accelerates the imitation and diffusion of technology and knowledge, thereby reducing the R&D and application costs of clean energy technologies and end-of-pipe treatment technologies. In this process, firms are more likely to benefit from green technology spillovers, which promotes the upgrading of the energy structure toward cleaner forms.

At the same time, a higher level of innovation agglomeration attracts high-tech industries, advanced manufacturing, and green environmental protection industries, which gradually replace highly polluting industries and traditional manufacturing. This increases the share of local green industries, optimizes the industrial structure, and reduces pollutant and carbon emissions at the source. In the process through which innovation agglomeration promotes sustained regional economic growth, local fiscal revenue also increases, enabling governments to invest more resources in environmental infrastructure, environmental monitoring, and the regulation of environmental behavior, thereby improving the overall efficiency of regional pollution and carbon governance.

In addition, as the level of regional development improves, residents' income grows steadily, and their demand for a better ecological environment increases accordingly. Coupled with the increasingly stringent assessment constraints imposed by higher-level governments on green development, local governments are compelled to strengthen environmental regulation and governance. This further tightens the control of high-energy-consuming and high-emission production activities, regulates various types of pollution discharge at the source, and promotes the coordinated development of pollution reduction and carbon mitigation. Therefore, after urban innovation agglomeration reaches a certain level, its inhibiting effect on the synergistic efficiency of pollution and carbon reduction is transformed into a promoting effect. Accordingly, this paper proposes the following hypothesis:

H1: Urban innovation agglomeration has an inverted U-shaped effect on the synergistic efficiency of pollution and carbon reduction.

3 EMPIRICAL DESIGN

3.1 Sample Selection and Data Sources

This study uses Chinese prefecture-level cities from 2007 to 2021 as the initial sample. To ensure the reliability of the empirical results, the data are processed as follows. First, observations with serious missing values are excluded. Second, all continuous variables are winsorized at the 1% level in both tails. After data processing, a balanced panel dataset covering 273 prefecture-level cities is obtained for the empirical analysis. The data are mainly drawn from the China City Statistical Yearbook, the China Statistical Yearbook, and the China Energy Statistical Yearbook.

3.2 Variable Definitions

3.2.1 Dependent variable: synergistic efficiency of pollution and carbon reduction

To more accurately capture the actual level of synergistic efficiency in pollution and carbon reduction, this study uses both the composite index calculated by the entropy method and the coupling coordination degree calculated by the coupling coordination model as dependent variables. These two indicators measure the synergistic efficiency of pollution and carbon reduction from the dimensions of "overall performance" and "degree of coordination," respectively.

The entropy method determines objective weights based on the information entropy of each indicator and is therefore suitable for constructing a comprehensive evaluation system. It can reflect the respective contributions of the pollution reduction system and the carbon reduction system to the overall level of synergistic pollution and carbon reduction. The coupling coordination model calculates the coupling coordination degree based on the standardized scores of the pollution reduction and carbon reduction systems, thereby capturing the interaction and coordination between the two systems. Therefore, using both the entropy-based composite index and the coupling coordination degree as dependent variables enables a more comprehensive measurement of the synergistic efficiency of pollution and carbon reduction.

In terms of data processing, this paper uses environmental pollution and carbon emission data at the prefecture-level city scale. After dimensionless processing, the entropy method is applied to calculate the comprehensive scores of the pollution reduction system and the carbon reduction system, with the corresponding entropy weights retained. The coupling coordination model is then used to calculate the coupling coordination degree, thereby obtaining the data on the synergistic efficiency of pollution and carbon reduction.

3.2.2 Explanatory variable: urban innovation agglomeration

Urban innovation agglomeration is an important driving factor for enhancing the synergistic efficiency of pollution and carbon reduction and achieving green development. Existing studies often use absolute-scale indicators, such as the total number of patents and R&D investment, to represent the level of urban technological innovation, or measure innovation agglomeration based on the administrative area of a city. However, these measurement methods have certain limitations. Absolute-scale indicators can reflect the quantity of innovation factors, but they cannot capture the spatial concentration of these factors. Meanwhile, measuring innovation agglomeration based on the administrative area of a city includes non-built-up spaces in the calculation. Since urban technological innovation activities are mainly concentrated in built-up areas, the agglomeration level measured using the entire administrative area may deviate from the actual spatial concentration of innovation factors.

Invention patents represent technological R&D output and, compared with other types of patents, can better reflect the quality of technological innovation in a region to some extent. Therefore, this paper uses the ratio of invention patent applications to built-up area to measure the level of urban innovation agglomeration. Specifically, urban innovation agglomeration is measured by the number of invention patent applications per unit of built-up area. In the data processing procedure, this study first collects patent application data for prefecture-level cities from 2007 to 2021, then screens out invention patent application data, and finally matches them with the built-up area of each prefecture-level city in the corresponding year to construct the urban innovation agglomeration indicator. A higher value of this indicator indicates a higher level of urban innovation agglomeration and a stronger agglomeration effect; conversely, a lower value indicates a weaker innovation agglomeration effect.

3.2.3 Control variables

Following the practice of existing studies[10], this study introduces a set of control variables that may affect the synergistic efficiency of pollution and carbon reduction into the econometric model, including fiscal decentralization, financial development, educational attainment, science and technology expenditure, and the level of environmental regulation. In addition, year fixed effects and city fixed effects are controlled for in the model. The specific variable definitions are reported in Table 1.

Table 1 Variable Selection and Definitions

Variable Type	Variable Type	Variable Type	Variable Type

Dependent variable	Synergistic efficiency of pollution and carbon reduction	*Ouhe*	Coupling degree between the composite environmental pollution index and urban carbon emissions, multiplied by 100
		Shangzhi	Entropy value obtained by the entropy method, multiplied by 100
Explanatory variable	Urban innovation agglomeration	*Inchuangxin*	Number of invention patent applications divided by built-up area, in logarithmic form
Control variable	Fiscal decentralization	Caizheng	Ratio of public fiscal revenue to public fiscal expenditure
	Financial development	Fin	Ratio of outstanding loans of financial institutions to GDP
	Educational attainment	*Inedu*	Ratio of education expenditure to fiscal expenditure
	Science and technology expenditure	*Tech*	Ratio of science and technology expenditure to fiscal expenditure
	Environmental regulation level	*Huanjing*	Frequency of words related to “environmental protection” in government work reports
	City	*City*	City dummy variable
	Year	*Year*	Year dummy variable

3.3 Model Specification

To test the research hypotheses, this paper first constructs a two-way fixed effects model to examine the relationship between urban innovation agglomeration and the synergistic efficiency of pollution and carbon reduction. In the model, urban innovation agglomeration is denoted by Inchuangxin, while the synergistic efficiency of pollution and carbon reduction is measured by Ouhe and Shangzhi, respectively.

$$\text{ouhe}_{i,t}=\alpha_0+\alpha_1 lnchuangxin_{i,t}+\alpha_2(lnchuangxin_{i,t})^2+\varphi X_{i,t}+u_i+\delta_t+\varepsilon_{i,t} \quad (1)$$

$$\text{shangzhi}_{i,t}=\alpha_0+\alpha_1 lnchuangxin_{i,t}+\alpha_2(lnchuangxin_{i,t})^2+\varphi X_{i,t}+u_i+\delta_t+\varepsilon_{i,t} \quad (2)$$

4 EMPIRICAL RESULTS AND ANALYSIS

4.1 Baseline Regression Analysis

The baseline regression results are reported in Table 2. Models M1 to M4 sequentially examine the impact of urban innovation agglomeration on the synergistic efficiency of pollution and carbon reduction, with the dependent variables measured by the coupling degree (Ouhe) and the entropy-based composite index (Shangzhi), respectively. After progressively introducing control variables, city fixed effects, and year fixed effects, the coefficient of the linear term of urban innovation agglomeration (Inchuangxin) is significantly positive, while the coefficient of its squared term ($Inchuangxin^2$) is significantly negative. Both coefficients pass the statistical significance tests, indicating a significant inverted U-shaped nonlinear relationship between urban innovation agglomeration and the synergistic efficiency of pollution and carbon reduction.

Overall, the baseline regression results verify the nonlinear relationship between urban innovation agglomeration and the synergistic efficiency of pollution and carbon reduction. They suggest that urban innovation agglomeration first inhibits and then promotes the synergistic efficiency of pollution and carbon reduction, thereby providing empirical support for Hypothesis H1.

Table 2 Baseline Regression Results of the Effect of Urban Innovation Agglomeration on the Synergistic Efficiency of Pollution and Carbon Reduction

Variables	*Ouhe*		*Shangzhi*	
	M1	M2	M3	M4
Inchuangxin	0.145^{*}	0.154^{**}	0.482^{**}	0.491^{**}
	(0.075)	(0.075)	(0.228)	(0.228)
Inchuangxin^2	-0.078^{***}	-0.065^{***}	-0.184^{***}	-0.170^{***}
	(0.017)	(0.018)	(0.053)	(0.049)
Caizheng		-1.056^{***}		-1.546^{*}
		(0.431)		(0.841)
Fin		-0.465^{***}		-0.780^{*}
		(0.122)		(0.457)
Inedu		0.286		0.243
		(0.231)		(0.627)
Tech		-14.661^{***}		-15.480
		(4.435)		(17.847)
_cons	95.520^{***}	97.003^{***}	92.830^{***}	94.714^{***}
	(0.103)	(0.478)	(0.144)	(1.289)
City FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
N	3724	3724	3724	3724

4.2 Robustness Checks

To further verify the robustness of the effect of urban innovation agglomeration on the synergistic efficiency of pollution and carbon reduction, this paper conducts robustness checks using the following two approaches.
First, the empirical sample is adjusted by excluding specific years. Considering that 2008 and 2020 may have been affected by special external shocks and other confounding factors, this study excludes the observations from 2008 and 2020 and reconstructs the panel dataset for regression analysis. The results show that the coefficient of the linear term of urban innovation agglomeration is significantly positive, while the coefficient of its squared term is significantly negative. These findings are consistent with the baseline regression results.
Second, the core explanatory variable is lagged by three periods. To alleviate potential concerns related to reverse causality and measurement bias, this paper conducts regression analysis after lagging the urban innovation agglomeration variable by three periods. The regression results show that the coefficient of the linear term of the three-period lagged innovation agglomeration variable remains significantly positive, while the coefficient of its squared term remains significantly negative, which is again consistent with the baseline regression results.
Overall, the regression results obtained from both robustness checks are consistent with the baseline findings, indicating that the inverted U-shaped effect of urban innovation agglomeration on the synergistic efficiency of pollution and carbon reduction is robust (Table 3).

Table 3 Robustness Checks

Variables	Excluding Specific Years		Three-Period Lag	
	Ouhe	*Shangzhi*	*Ouhe*	*Shangzhi*
	M1	M2	M3	M4
Inchuangxin	0.200^{**}	0.532^{***}	0.183^{**}	0.581^{***}
	(0.097)	(0.033)	(0.088)	(0.136)
Inchuangxin^2	-0.076^{***}	-0.167^{***}	-0.115^{***}	-0.235^{***}
	(0.022)	(0.033)	(0.020)	(0.032)
Controls	Yes	Yes	Yes	Yes
_Cons	95.745^{***}	92.950^{***}	95.807^{***}	92.978^{***}
	(0.105)	(0.156)	(0.104)	(0.160)
Year FE	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes
N	2686	2686	2631	2631

5 CONCLUSIONS AND POLICY IMPLICATIONS

From the perspective of agglomeration economics, this paper uses panel data from 273 prefecture-level cities in China from 2007 to 2021 to examine the impact of urban innovation agglomeration on the synergistic efficiency of pollution and carbon reduction. The results show that there is a significant inverted U-shaped nonlinear relationship between urban innovation agglomeration and the synergistic efficiency of pollution and carbon reduction. This finding suggests that, at the early stage of agglomeration, problems such as congestion of innovation factors, insufficient investment in green innovation, and a relatively high share of energy-intensive industries tend to dominate. At this stage, the increase in emissions caused by economic expansion exceeds the emission-reduction effect generated by technological progress, thereby inhibiting the synergistic efficiency of pollution and carbon reduction. However, once the level of agglomeration exceeds a certain threshold, the effects of green technology spillovers and industrial structural transformation and upgrading gradually come into play, thereby promoting the synergistic efficiency of pollution and carbon reduction.
Based on the above findings, the policy implications of this study can be summarized from the following two aspects.
First, the scope and degree of innovation factor agglomeration should be reasonably defined to avoid congestion of innovation factors. In the process of building innovation-oriented cities, local governments should assess and determine the appropriate range of innovation agglomeration according to local resource endowments and urban carrying capacity. They should avoid blindly pursuing the expansion of agglomeration scale, which may lead to congestion of innovation factors and the waste of innovation resources. For cities with a relatively low level of agglomeration, efforts should be made to improve innovation platforms, cultivate innovation entities, and strengthen innovation infrastructure, so as to attract innovation factors and help these cities move more quickly beyond the turning point of the inverted U-shaped relationship. For cities with a relatively high level of agglomeration, it is necessary to reasonably guide the flow of innovation factors, optimize the spatial layout of innovation through cross-regional coordination, improve the allocation efficiency of innovation factors, and continuously release the synergistic effects of pollution and carbon reduction.
Second, region-specific policies should be implemented to narrow the gap in green development across regions. Since Chinese cities differ greatly in terms of technological innovation capacity, industrial structure, and environmental governance capability, a one-size-fits-all governance approach should be avoided. Instead, differentiated guidance and targeted policy implementation should be adopted. For cities with weak innovation capacity and a high proportion of traditional industries, priority should be given to addressing weaknesses in basic innovation capacity. These cities should cultivate distinctive green industries based on local resource advantages and promote pollution and carbon reduction through low-cost and applicable green technologies. For cities with abundant innovation resources and a relatively high

level of green development, policy efforts should focus on green technological innovation, allowing these cities to play a leading, demonstrative, and spillover role. They should also export technology, talent, and experience to surrounding cities, thereby promoting the coordinated transformation of neighboring areas. In addition, regional coordination mechanisms should be established to integrate the spatial allocation of innovation factors with joint ecological and environmental governance, narrow inter-city gaps in the synergistic efficiency of pollution and carbon reduction, and ultimately achieve overall improvement.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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