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Urban Primacy, Innovation Capacity, and Spatial Spillover Effects: An Empirical Analysis Based on the Spatial Durbin Model

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Abstract:
Against the backdrop of innovation-driven development, this research explores how urban innovation capacity exhibits spatial spillover effects, particularly in relation to urban primacy. Drawing on panel data from 33 cities in Jiangsu, Hubei, and Sichuan provinces between 2002 and 2022, this study constructs a Spatial Durbin Model (SDM) incorporating bi-directional fixed effects and spatial distance weights. The analysis controls economic scale, industrial structure, R&D expenditure, education level, urban size, foreign direct investment, and infrastructure. Results reveal pronounced spatial heterogeneity: Jiangsu exhibits significant positive spatial linkages, where urban primacy suppresses local and overall innovation but slightly promotes that of neighboring areas, indicating a "coordinated-driven" pattern. In contrast, Hubei exhibits negative spatial correlation, with primacy effects being statistically insignificant. In Sichuan, primacy positively affects both local and neighboring innovation, yet the overall spatial spillover remains negative, suggesting a "siphon effect." Policy implications highlight the need for strengthening monocentric structures in less developed regions to foster aggregate innovation, while more advanced areas should transition toward polycentric urban systems to mitigate siphoning and promote balanced, high-quality development.

Keywords: Innovation; urban primacy; spatial spillover.

1. Introduction

The developmental trajectories of many countries have demonstrated that, beyond a certain stage of growth, economies must transition from factor-driven to innovation-driven models. As China's economic aggregate continues to expand, a corresponding shift in the development paradigm has become imperative.

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The Chinese government has increasingly emphasized the central role of innovation in national modernization strategies, introducing a series of policies aimed at strengthening innovation capacity. In this context, identifying the key drivers of innovation and exploring effective means to enhance it have become central concerns for both domestic and international scholars.

Existing research highlights a close relationship between urban development and innovation capacity. Given the presence of siphon effects across cities, a critical question arises: does urban innovation also exhibit such siphoning, or can innovation-rich cities exert positive spillovers akin to industrial synergy, thereby fostering innovation in neighboring areas? Prior studies have shown that urban primacy is significantly associated with the strength of either siphoning or synergistic effects. This study, therefore, takes urban primacy as the core explanatory variable and employs spatial econometric modeling to empirically examine the spatial spillover effects of urban innovation capacity.

This paper makes two main contributions: first, it introduces urban primacy as a key explanatory factor in analyzing its impact on innovation capacity; second, it investigates regional heterogeneity by selecting three provinces with distinct characteristics. The findings aim to offer policy insights for Chinese urban planners, helping to determine whether monocentric or balanced development strategies are more suitable based on specific regional conditions and geographical contexts.

2. Literature Review

2.1 Review of Research on Urban Innovation Capacity and Its Spatial Spillovers

Under China's innovation-driven development strategy, enhancing urban innovation capacity has become a key indicator of high-quality regional development. Whether existing inter-city spatial spillovers are also reflected in innovation diffusion has attracted considerable scholarly attention. According to Romer's endogenous growth theory, knowledge and innovation generate considerable externalities, enabling their influence to extend beyond administrative limits and contribute to regional synergy through spatial spillovers. Building on this insight, recent studies have increasingly examined the mechanisms of innovation interaction among cities from the perspectives of geographic proximity, institutional coordination, and technological linkages.

Existing research on spatial spillover effects of innovation capacity mainly focuses on spatial associations between innovation and influencing factors such as patent transfers, environmental regulation, and digital technology. For example, Zhou et al. constructed a spatial econometric model based on data from 41 cities in the Yangtze River Delta and found that environmental regulation not only significantly boosts local innovation capacity but also generates positive spatial spillover effects through proximity-based interaction mechanisms [1]. Chen et al., focusing on the Pearl River Delta, revealed that geographic distance, technological proximity, and institutional similarity play important roles in digital innovation linkages, with core cities like Shenzhen and Guangzhou exerting significant radiative effects [2]. Furthermore, some scholars have used SDM to analyze urban patent transfer networks, demonstrating that cities occupying central or structural hole positions significantly enhance both their own and neighboring cities' innovation capacities. Such technological circulation networks serve as vital channels for knowledge sharing and regional collaboration [3].

Meanwhile, existing studies also point to heterogeneity in the determinants of innovation spillovers. Zhou et al. noted that urban expansion—reflected in boundary extensions, population density declines, and area increases—can suppress innovation both locally and in neighboring cities [1]. Additionally, some scholars employed a difference-in-differences (DID) model using panel data from 284 Chinese prefecture-level cities (2007–2019) to assess the impact of National Innovation Demonstration Zone policies. Their findings indicate that these policies significantly improve urban innovation efficiency, although the outcomes exhibit spatial and institutional heterogeneity [4].

2.2 Research on Urban Primacy

In recent years, as urban agglomerations and metropolitan areas have become key drivers of regional innovation and economic growth, the role of urban primacy within innovation networks has attracted growing scholarly attention. Urban primacy reflects not only a city's comprehensive influence in terms of geography, economy, knowledge, and technological innovation but also its pivotal function as a hub and leader within regional networks.

For example, taking the Nanjing metropolitan area as a case study, scholars constructed a multi-level collaborative structure consisting of a Knowledge Innovation Network and a Technology Innovation Network. Their empirical analysis revealed a spatial differentiation pattern of "core city–peripheral city", highlighting that Nanjing, as the primate city, has consistently maintained a dominant role in the innovation network [5]. The study also found that both technological and knowledge innovation generate positive spatial spillovers, with the effects being stronger for the primate city. These findings provide an important foundation for examining the relationship between urban primacy and innovation capacity in this paper.

Likewise, the study by Chen et al. on digital technology innovation linkages in the Guangdong–Hong Kong–Macao Greater Bay Area demonstrated the sustained centrality of Guangzhou and Shenzhen within patent transfer networks.. They further emphasized that institutional and technological proximity significantly strengthen innovation linkages, with urban primacy serving as a fundamental platform in forming an "innovation flow axis" [2].

In summary, existing research on spatial spillovers of innovation capacity and urban primacy largely suggests that primate cities foster regional innovation networks through resource agglomeration and technological diffusion. However, notable limitations remain, particularly the lack of attention to inter-regional heterogeneity across different Chinese city clusters. To address this gap, the present study selects three representative provinces in China and, based on panel data from 2002 to 2022, employs the SDM to empirically investigate the spatial spillover effects of urban primacy on innovation capacity, with particular emphasis on regional heterogeneity.

3. Methodology

3.1 Model Selection

In studies on regional economic growth and technological innovation, spatial effects are pervasive. On the one hand, economic development and innovation activities across cities exhibit strong spatial correlation—meaning that a city's innovation level depends not only on its own resource endowments and economic conditions but may also be influenced by the diffusion and spillovers from neighboring regions. On the other hand, neglecting such spatial dependence in estimation risks biased coefficients and misleading conclusions when using conventional panel regression models.

To address this issue, the present study adopts the SDM as the core econometric framework. The SDM extends the traditional Spatial Autoregressive Model (SAR) and the Spatial Error Model (SEM). Specifically, it incorporates not only the spatial lag of the dependent variable but also the spatial lags of the explanatory variables, thereby capturing the spillover effects of the control variables. This specification allows for the simultaneous identification of two competing mechanisms: the "siphon effect" and the "synergy effect."

To mitigate omitted variable bias arising from unobserved city-specific characteristics and time trends, the model introduces two-way fixed effects after conducting a Hausman test. City fixed effects account for unobservable, time-invariant factors such as institutions and geography, while year fixed effects absorb macroeconomic cycles and nationwide policy shocks. These adjustments enhance the robustness of the estimates. Accordingly, the baseline SDM is specified as follows [6]:

$$innovation_{it} = \rho W innovation_{it} + \beta X_{it} + \theta W X_{it} + \mu_i + \lambda_t + \epsilon_{it} \quad (1)$$

Here, $innovation_{it}$ denotes the dependent variable, representing the innovation level of city i in year t measured by the Urban Innovation Index. X_{it} is a vector of explanatory and control variables. W is the spatial weight matrix, defined in this study as the inverse of the geographical distance between cities. $\mu_i and \lambda_t$ capture city and year fixed effects, respectively, while ϵ_{it} represents the random disturbance term.

3.2 Variable Selection

Drawing upon earlier research, this paper employs the Urban Innovation Index as the dependent variable, while urban primacy is introduced as the core explanatory variable. Control variables include city Gross Domestic Product (GDP), the share of the tertiary sector in GDP, the proportion of scientific expenditure in fiscal expenditure, the number of universities, registered population size, foreign direct investment (FDI), and per capita road area. All data are derived from the China City Statistical Yearbook [7-9]. The measurement of urban primacy is based on Ioannou's approach, constructed using city-level GDP [10].

To further explore the heterogeneity of the spatial spillover effects of urban primacy under different development patterns, this study selects 33 cities across Jiangsu, Hubei, and Sichuan provinces for grouped estimation. Jiangsu represents a typical "polycentric" model in China, where the primacy of the provincial capital Nanjing is relatively low, and Suzhou has at times surpassed Nanjing in primacy. Overall, Jiangsu is characterized by a polycentric structure with large disparities among cities. Hubei, in contrast, exemplifies the "strong provincial capital" model in eastern China, with Wuhan accounting for more than one-third of provincial GDP, reflecting a high degree of resource concentration alongside relatively balanced development in other areas. Sichuan, located in western China, also represents a "strong provincial capital" model, but with pronounced resource bias: Chengdu dominates while the rest of the province lags significantly behind. Based on these distinctive provincial characteristics, the empirical results for Jiangsu, Hubei, and Sichuan will be compared to analyze heterogeneity.

4. Estimation Results

4.1 Estimation Results for Jiangsu Province

The estimation results of the SDM model for Jiangsu Province are presented in Table 1.

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Table 1. Estimation results for Jiangsu province

Variables	Main Effect	Spatial Lag Term	Spatial Error Coefficient	Direct Effect	Indirect Effect	Total Effect
Urban Primacy	-4,465.0780**	-9,131.48		-5,501.7147***	-17,847.7420**	-23,349.4567**
GDP	-205.2309**	670.6169***		-158.9804*	929.6708***	770.6905***
Share of Tertiary Industry in GDP	-116.6206	-1,674.1156*		-215.3578	-2,685.7314**	-2,901.0892**
Scientific Expenditure	100.4018***	-101.4092***		97.4659***	-95.9754*	1.4905
Number of Universities	13.7689**	-16.4982		11.5224	-18.3581	-6.8357
Registered Population	2,479.5215***	-1,026.24		2,533.1141***	257.1711	2,790.29
Actual FDI Utilized	-30.8446	-23.2931		-35.0023	-43.3145	-78.3168
Per Capita Road Area	-10.5926**	-37.8529***		-14.9554***	-68.7981***	-83.7536***
Spatial Autoregressive Coefficient			0.4418***			

Notes: The dependent variable is the Urban Innovation Index. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

As shown in Table 1, the spatial autoregressive coefficient (ρ=0.4418) is significantly positive at the 1% level, indicating strong spatial linkages in technological innovation across Jiangsu's cities. In other words, an improvement in innovation capacity in one city tends to stimulate innovation in its neighboring cities.

Regarding urban primacy, the coefficient is significantly negative, suggesting that excessively high primacy suppresses local innovation, reflecting a clear "siphon effect." The direct effect is likewise significantly negative, further confirming that excessive urban primacy inhibits local innovation capacity. By contrast, the indirect effect is significantly positive, implying that while core cities may attract resources away from themselves, they simultaneously promote innovation in surrounding areas through spillover effects. Nevertheless, the total effect remains significantly negative, suggesting that in Jiangsu, the siphon effect of urban primacy outweighs its spillover benefits, leading to an overall inhibitory impact on regional innovation.

With respect to the control variables, the level of economic development exerts a significant negative effect on local innovation but demonstrates a strong positive impact on neighboring cities, highlighting the existence of cross-regional resource spillovers. Scientific expenditure significantly enhances local innovation but fails to generate meaningful benefits for surrounding areas, indicating that fiscal investment remains primarily localized. The number of higher education institutions significantly improves local innovation capacity, underscoring the critical role of higher education resources. Finally, population size exerts a positive influence on innovation, suggesting that both market scale and human capital serve as key drivers of urban innovation.

4.2 Estimation Results for Hubei Province

The estimation results of the SDM model for Hubei Province are presented in Table 2.

Table 2. Estimation results for Hubei province

Variables	Main Effect	Spatial Lag Term	Spatial Error Coefficient	Direct Effect	Indirect Effect	Total Effect
Urban Primacy	408.7358	419.3732		405.732	63.7981	469.5301
GDP	-80.9842***	110.7915***		-90.4154***	103.6699***	13.2545
Share of Tertiary Industry in GDP	-87.1515	688.4285***		-113.5101	475.9988***	362.4887***

Scientific Expenditure	6.4062	0.0091		7.2348	-2.8791	4.3558
Number of Universities	4.4389***	1.868		4.3313***	-0.4946	3.8367
Registered Population	1,020.7036***	-3,746.8201***		1,231.4353***	-2,801.3956***	-1,569.9603***
Actual FDI Utilized	6.9310*	24.4858		6.1133	14.3826	20.4959*
Per Capita Road Area	1.0401	0.372		0.9362	-0.2497	0.6866
Spatial Autoregressive Coefficient			-0.5182***			

As indicated in Table 2, the spatial autoregressive coefficient for Hubei Province (ρ=−0.5182) is significantly negative at the 1% level, suggesting that innovation in Hubei displays spatial competition effects, whereby advancements in one city's innovation are associated with declines in neighboring cities. With respect to urban primacy, both the direct and indirect effects are statistically insignificant, suggesting that urban primacy in Hubei neither generates a significant "siphon effect" nor a "synergy effect" on innovation. Turning to the control variables, similar to Jiangsu, economic development significantly suppresses local innovation, while its indirect effect is positive, implying that economic growth may still generate spillover benefits through regional linkages. The share of the tertiary industry in GDP exerts a significantly positive total effect, demonstrating the supporting role of industrial upgrading in promoting innovation. The number of higher education institutions has a significantly positive direct effect, highlighting the importance of educational resources. Population size strongly enhances local innovation capacity, yet its spatial spillover effect is negative, suggesting that excessive population concentration may generate a "siphon effect."

Overall, innovation in Hubei is driven by a combination of local accumulation and regional spillovers, though excessive population agglomeration also introduces negative externalities.

4.3 Estimation Results for Sichuan Province

The estimation results of the SDM model for Sichuan Province are presented in Table 3.

Table 3. Estimation results for Sichuan province

Variables	Main Effect	Spatial Lag Term	Spatial Error Coefficient	Direct Effect	Indirect Effect	Total Effect
Urban Primacy	437.4084**	1,582.1205**		385.6415*	976.5922**	1,362.2337***
GDP	-10.0582**	14.4484		-11.3025***	13.2933*	1.9908
Share of Tertiary Industry in GDP	-2.3905	34.6837		-0.9619	26.1498	25.1879
Scientific Expenditure	2.1792	-1.5002		2.5041	-2.0279	0.4761
Number of Universities	2.4023***	-3.4391**		2.4863***	-3.1881***	-0.7018
Registered Population	-172.2388***	164.233		-177.5585***	186.5366	8.9781
Actual FDI Utilized	0.2477	1.9807		0.2452	1.4138	1.659
Per Capita Road Area	0.3865	0.5522		0.3284	0.3469	0.6753
Spatial Autoregressive Coefficient			-0.4223***			

As shown in Table 3, the spatial autoregressive coefficient for Sichuan Province (ρ=−0.4223) is significantly negative at the 1% level, indicating that, similar to Hubei, innovation capacity in Sichuan exhibits spatial competition effects. However, in terms of urban primacy, the direct, indirect, and total effects are all significantly positive. This suggests that under conditions where surrounding cities maintain relatively low innovation levels, core cities in Sichuan not only enhance their own innovation capacity but also exert strong positive spillover effects on neighboring

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cities, thereby reflecting a clear "synergy effect." In other words, although core cities may simultaneously generate siphon effects by attracting resources, higher urban primacy in Sichuan ultimately promotes overall regional innovation. Regarding the control variables, GDP exerts effects similar to those observed in Hubei and Jiangsu. Industrial upgrading and scientific expenditure do not significantly affect innovation, implying limited transformation efficiency. The number of higher education institutions strongly promotes local innovation but produces crowding-out effects on surrounding areas, reflecting the high concentration of educational resources. Population size suppresses local innovation yet may contribute positively to neighboring cities through spillover channels.

Overall, innovation-driven development in Sichuan demonstrates a pattern of "resource concentration with limited spillovers."

4.4 Heterogeneity Analysis

In terms of urban primacy, the total effect in Jiangsu Province is significantly negative, whereas the coefficients for Hubei and Sichuan are significantly positive. This indicates that Jiangsu exhibits a siphon effect of primate cities, while Hubei and Sichuan display a "synergy effect." A possible explanation lies in the marked economic disparities within Jiangsu, where innovation resources are concentrated in a few core cities (e.g., Nanjing and Suzhou), while Hubei and Sichuan are characterized by a "single-city dominance" structure.

Regarding the spatial autoregressive coefficient, Jiangsu shows a significantly positive value, whereas Hubei and Sichuan show significantly negative ones. This suggests that, despite the siphon effect in Jiangsu, the overall positive spatial correlation indicates continued intercity linkages in innovation. By contrast, in Hubei and Sichuan, although urban primacy significantly promotes local innovation, the negative spatial correlation reveals that such development suppresses innovation in neighboring cities, reflecting a pronounced siphon effect.

In summary, the spatial spillover effects of urban primacy on innovation exhibit significant heterogeneity. This paper argues that the polycentric urban structure and relatively complete industrial chains in Jiangsu are conducive to forming synergy effects, whereas the monocentric patterns of Hubei and Sichuan tend to foster innovation competition, whereby core cities siphon resources from surrounding areas.

5. Conclusion

Using the SDM method, this study conducts a heterogeneity analysis of the spatial spillover effects of urban primacy on innovation capacity in three Chinese provinces—Jiangsu, Hubei, and Sichuan. The results indicate significant heterogeneity in the spatial spillover effects of urban primacy. In regions such as Jiangsu, characterized by higher levels of economic development, relatively complete industrial chains, and a polycentric rather than monocentric structure, urban innovation capacity exhibits a strong "synergy effect," whereby the improvement of innovation capacity in one city promotes innovation in others. By contrast, in regions such as Hubei and Sichuan, where regional development is uneven and resources are highly concentrated in the primate city, the effects resemble a "siphon effect." In these cases, the enhancement of innovation in the primate city suppresses innovation in other cities, though overall the development of core cities still contributes positively to regional innovation capacity.

Accordingly, regional policymakers should carefully align development strategies with the local stage of economic development. For less-developed regions, it is advisable to prioritize resource concentration in core cities to raise overall regional development, rather than prematurely adopting a polycentric strategy that may disperse resources and slow growth. For regions at higher stages of economic development, fostering a polycentric urban structure becomes essential to avoid over-concentration in a single city and to achieve more balanced, high-quality growth. Moreover, in Sichuan, where spatial competition is evident, optimizing the spillover pathways of core cities is necessary to mitigate competitive pressures.

This study also has several limitations. Due to constraints on data availability, the selection of control variables is incomplete; factors such as regional information connectivity and policy openness were not incorporated into the model. Similarly, the measure of educational level is imperfect, as data limitations prevented the use of university students per 10,000 residents as a control variable. Future research will aim to overcome these limitations and further deepen the analysis.

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