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*Research Article*

# Evolutionary Analysis of Innovation Development in a Metropolitan Area from a Symbiosis Perspective: Empirical Research on the Shanghai Metropolitan Area

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Promoting the innovative development of cities in the metropolitan area holds great significance for China's implementation of the "innovation-driven development" strategy. According to symbiosis theory, this paper constructed a city-based Lotka-Volterra symbiosis model and innovation-level index system. We used the Shanghai metropolitan area as a sample for empirical analysis to explore the evolution of the comprehensive development level of urban innovation under different symbiotic relationships. The research results showed that under a reciprocal relationship, the innovative development of core city and node cities was higher than the actual level; under a mutual inhibition symbiosis or parasitic symbiotic relationship, the innovative development of core city and node cities was lower than the actual level; and under an independent symbiotic relationship, the innovative development of the core city was higher than the actual level, while that of the node cities was lower than the actual level.

## 1. Introduction

As China's economy has shifted from a stage of rapid growth to a stage of high-quality development, the traditional factor-driven economic growth model no longer meets China's development requirements. In this context, the 18th National Congress of the Communist Party of China proposed an innovation-driven development strategy, emphasizing that science and technology innovation is strategic support for improving social productivity and comprehensive national power, and it must be placed at the core of the overall national development. As an important aspect of innovation-driven development, regional innovation is a key area that the government pays attention to. The "Outline of the National Innovation-Driven Development Strategy" clearly pointed out that the development of regional innovation in China not only relied on the construction of regional science and technology demonstration areas but also required the government to optimize the allocation of innovation resources to achieve the coordinated development of regional innovation. On this basis, given that metropolitan areas are regional resource-gathering centers, the improvement of their innovation capacity holds great significance for regional innovation development. Numerous studies have shown that the innovative development of each city in metropolitan areas not only depends on the development conditions of the city itself but is also closely related to the innovation linkage between cities [1–4]. In China, the economic, cultural, and political connections between cities in the region have formed a huge and complex metropolitan area. With development plans such as the "Development Plan for the Yangtze River Delta City Cluster," the "Outline of the Beijing-Tianjin-Hebei Coordinated Development Plan," and the "Guiding Opinions on the Cultivation and Development of Modern Metropolitan Areas," the development of China's metropolitan areas has been greatly accelerated and the innovation linkages between cities have also been strengthened. As a result, urban innovation in the metropolitan area has set a development trend of clustering and networking, with megacities as the center [5]. In this context, the symbiotic relationships among cities in the metropolitan area encourage further innovation development and will inevitably have an impact on the level of comprehensive innovation development of the city [6]. Therefore, studying the impact of this symbiotic relationship among cities in the metropolitan area on the comprehensive innovation development level of the city holds great significance for the formulation of a reasonable development strategy to promote the development of urban innovation in metropolitan areas.

## 2. Related Reference Review

Integrating ecological concepts into urban innovation development and actively creating an urban innovation ecosystem has become the government's preferred strategy for promoting regional innovation development [7]. In reality, understanding how to coordinate the symbiotic relationships among cities, as well as how to enhance the overall development of the innovation ecosystem, in order to achieve the synergistic development of innovations in the metropolitan area has presented a significant challenge for the government in the process of regional innovation development. Guided by these questions, related innovation ecosystems, symbiotic relationships among subjects, and the innovative development of metropolitan areas have become popular research topics for scholars.

*2.1. Innovation Ecosystem Study.* The ecosphere was first studied in biology, and Jucevicius argued that the "ecosphere" is actually a complex system with a self-regulating function formed by the interaction of life subjects in an inorganic environment [8]. Pan and Yang summarized that the ecosphere is characterized by the diversity of population tribes, mutual symbiosis, and ecological self-reproduction [9]. With the deepening of research, based on the practical significance and characteristics of the ecosystem, this theory has been widely used in the study of the relationship among micro-innovative entities, including enterprises, universities, scientific research institutions, and service institutions. Ander argued that in a corporate innovation ecosystem, business can reduce operating risks and expand returns through resource sharing [10]. Wu et al. constructed a spiral innovation ecosystem by combining government, enterprises, universities, and technology business incubators. They found that the diversity and differentiation of innovation agents were important features of the innovation ecosystem [11]. Taking the development of enterprise agglomeration as a logical starting point, Xu and Ren found that the operating mechanism of the innovation ecosystem within a central city was composed primarily of a symbiosis mechanism, a benefit distribution mechanism, and an environmental matching mechanism [12]. Based on the Lotka-Volterra model, Peng et al. found that the introduction of universities can effectively facilitate the transfer of subject knowledge in the innovation ecosystem [13]. Li proposed that the integration of industry, innovation, capital, and service chains can effectively enhance the energy level of the innovation ecosystem. They argued that the essence of the integration of the four was the process of deepening the synergy among enterprises, universities, research institutions, and service institutions [14].

*2.2. Study of Symbiotic Relationships.* As an important condition and evolutionary guarantee for the formation of an innovation ecosystem, symbiosis offers great research value. The theory of symbiosis was first proposed by German mycologist De Berry. This theory elaborates primarily on the phenomenon that different populations interact with each other and evolve synergistically to achieve symbiosis and coprosperity. Based on the practical significance of this theory, many scholars have extended it to the field of innovation ecosystems. According to the theory of symbiotic relationships, Moore argued that the best relationship among enterprises should be symbiotic evolution, rather than the traditional relationship of cooperation and competition [15]. According to Li et al., the essence of the innovation ecosystem is a community formed by the mutual influence and symbiotic evolution of innovation subjects [16]. Zahra and Nambisan speculated that the symbiotic relationship between subjects is the foundation of the innovation ecosystem, and the core enterprise optimizes the innovation development environment of satellite enterprises [17]. Long et al. constructed an innovation ecosystem consisting of government, technology alliances, and intermediary organizations and found that a reciprocal and symbiotic ecological relationship is conducive to enhancing the efficiency of knowledge transfer [18]. Gu and Xie used symbiosis theory to study the Toyota business ecosystem, and the results showed that cocreation and value sharing were the prerequisites for the existence of symbiosis [19]. Wu et al. analyzed the symbiotic relationship of subjects in the patent innovation ecosystem, and they found that the symbiotic relationship among subjects had an important impact on patent growth [20]. Hao and Ren calculated the coefficient of symbiosis between enterprise subjects and concluded that reciprocal symbiosis was the best way to develop an innovation ecosystem [21].

*2.3. Study of Innovative Development of Metropolitan Areas.* In recent years, against the background of the flourishing development of metropolitan areas, including the Yangtze River Delta, Beijing-Tianjin-Hebei, Guangdong, Hong Kong, and Macao, research on their innovative development has garnered increasing scholarly attention. Using the Guangdong–Hong Kong–Macao Greater Bay Area as a research object, Dong et al. concluded empirically that reducing the cost of collaborative innovation among cities can improve the innovation efficiency of cities [22]. Through cohesive subgroup analysis and knowledge complexity measurement, Xu et al. found that innovation synergy among cities is conducive to promoting regional innovation development. They proposed that a regional innovation community with a division of labor and collaboration should be developed to enhance the innovation competitiveness of cities [23]. On the basis of the perspective of an evolutionary game, Liu and Yan found that the initial state of innovation agents, evolutionary environment, and synergistic mechanism all can influence the evolutionary path of collaborative innovation in urban clusters [24]. Based on an exponential stochastic model, Wang et al. found that knowledge elements, economic development, and research investments were important factors influencing city innovation synergy. Their results showed that the government should guide cities to develop innovation strategies based on local conditions to help build an interactive and synergistic innovation network [25]. Li and Zhang evaluated the innovation ecological synergy of three major metropolitan areas in China. They concluded that the variability of innovation coordination in urban agglomerations is determined mainly by government environmental regulation, science, and technology innovation support and the degree of market competition [26].

This body of literature has enriched the theory of innovation ecosystems, symbiotic relationships, and the innovative development of metropolitan areas. This research still has shortcomings in the following areas: first, the existing research on innovation ecosystems and symbiotic relationships has focused mainly on the research of microsubjects, including enterprises, scientific research institutions, and universities, whereas relatively few macrostudies have focused on cities. Second, in actual situations, the innovation relationship between cities is relatively complex and diverse, whereas the existing research has focused mainly on the impact of coordinated development between cities on regional innovation and has failed to consider the impact of other possible relationships on urban innovation development comprehensively. Third, the existing research on urban innovation has ignored the factors of urban heterogeneity and has failed to fully integrate the regional distribution characteristics of core cities and node cities in China's metropolitan circle in its analysis.

This study addresses the shortcomings of the research conducted to date. First, to better reflect the theoretical contribution of this study, from the perspective of a symbiotic relationship, we selected the entire city as the research object and established a symbiotic evolution model of core cities and node cities in the urban innovation ecosystem. Second, we selected the Shanghai metropolitan area as an example to conduct an empirical analysis and analyzed the evolutionary trend of the comprehensive development level of urban innovation under different symbiotic relationships through simulation. There are two main innovations and contributions of this article. The first is that it takes the entire city as the research object by analyzing the impact of symbiotic relationships on regional innovation development from a macro perspective and providing theoretical support for the government to coordinate the symbiotic relationship among cities in the process of regional innovation development. Second, we fully integrated the regional distribution characteristics of core cities and node cities in China's metropolitan area to study the urban symbiotic relationship and analyzed the evolutionary trend of the comprehensive development level of urban innovation under different symbiotic relationships to provide a reference for the innovation development of China's metropolitan areas.

## 3. Symbiosis Model Construction and Parameter Estimation

*3.1. Theoretical Foundations.* The Lotka-Volterra model in symbiosis theory was first established by the American scholar Lotka (1925) and the Italian scholar Volterra (1926). This model was first applied to the study of the interaction between different populations in ecology. In recent years, it has been widely cited in the field of innovative ecological management. Existing studies have suggested that symbiotic relationships such as reciprocal symbiosis, mutual inhibition symbiosis, independent symbiosis, and parasitic symbiosis are common among ecological agents, and the symbiotic relationship is determined by the symbiotic coefficients ($u_{ij}$, $i \neq j$) [27]. The details are shown in Table 1.

*3.2. Model Construction.* Given that the innovative development behavior of cities in a metropolitan area is consistent with the symbiotic ecological characteristics of natural populations and that this model has been applied to study the symbiotic relationships among multiple agents in various fields of economic management, such as technological innovation, urban development, and knowledge synergy, we used the Lotka-Volterra model to explore the symbiotic relationship among cities in the metropolitan area and its impact on the development of comprehensive innovation. In this study, we categorized the cities in the metropolitan area into a core city ($x1$) and node cities ($x2$, $x3$). A core city is a megacity with a huge economic scale, rich innovation resources, and obvious competitive advantages over neighboring cities. A node city is a city that is geographically close to the core city and is greatly affected by the spillover effect of the core city in terms of its economy [28]. The model assumptions are as follows.

*Assumption 1.* Status Constraints.

Metropolitan areas did not have any status constraints on core cities or status constraints on node cities. In the process of regional development, because node cities did not have the relatively important urban status of core cities, they were constrained relative to core cities in areas such as external policy support, resource allocation, and talent flow, which in turn affected their level of comprehensive innovation development.

*Assumption 2.* Symbiotic Relationship.

In the process of regional innovation development, the innovation development of cities was influenced by other cities. According to symbiotic relationship theory, we found reciprocal symbiosis, mutual inhibition symbiosis, independent symbiosis, and parasitic symbiosis between core cities and node cities. In this relationship, "⟶" is characterized as the interaction between subjects, "+" indicates that the coefficient of symbiosis between two subjects is

Table 1: Symbiotic relationships.

| Symbiotic coefficients | Symbiotic relationships | Definition |
|---|---|---|
| $u_{ij} > 0, u_{ji} > 0$ | Reciprocal symbiosis | Population $i$ and population $j$ reinforce each other for mutual development |
| $u_{ij} > 0, u_{ji} > 0$ | Mutual inhibition symbiosis | Population $i$ and population $j$ inhibit each other and hinder each other's development |
| $u_{ij} = 0, u_{ji} = 0$ | Independent symbiosis | Population $i$ and population $j$ are independent of each other and do not affect each other's development |
| $u_{ij} < 0, u_{ji} > 0$ *or* $u_{ij} > 0, u_{ji} < 0$ | Parasitic symbiosis | Population $i$ promotes the development of population $j$, while population $j$ inhibits the development of population $i$ |

greater than 0, and "–" indicates that the coefficient of symbiosis between two subjects is less than 0.

*Assumption 3.* Evolutionary Patterns.

In the initial stage of comprehensive urban innovation development, its growth showed a relatively obvious upward trend. As the level gradually increased, the growth rate of comprehensive innovation development level would decrease because of the constraints of the relationship and development (R&D) capacity of urban subjects and technology costs. Thus, the growth process of comprehensive innovation development level of cities in the metropolitan area followed the logistic law [29].

*Assumption 4.* Evolutionary Dynamics.

We did not find any status constraints on core cities. The amount of change in its level of comprehensive innovation development at the moment is $dx_1/dt = r_1x_1$, while the node city is affected by the status constraint, and the amount of change at the moment is $dx_i/dt = r_ix_i(1 - x_i/N_i) \quad (i = 2, 3)$.

According to these assumptions, the Lotka-Volterra model of cities ($x_1$, $x_2$, $x_3$) constructed in this study is as follows:

$$\begin{cases} \dfrac{dx_1}{dt} = r_1x_1\left(1 + u_{12}\dfrac{x_2}{N_2} + u_{13}\dfrac{x_3}{N_3}\right), \\ \dfrac{dx_2}{dt} = r_2x_2\left(1 - \dfrac{x_2}{N_2} + u_{21}x_1 + u_{23}\dfrac{x_3}{N_3}\right), \\ \dfrac{dx_3}{dt} = r_3x_3\left(1 - \dfrac{x_3}{N_3} + u_{31}x_1 + u_{32}\dfrac{x_2}{N_2}\right). \end{cases} \tag{1}$$

where $N_i$ ($i = 1, 2, 3$) represents the highest level of comprehensive innovation development of the city under the constraints of objective conditions; $u_{ij}$ represents the coefficient of symbiosis between cities, which indicates the degree of influence of city $i$ on the innovative development of city $j$; and $r_i > 0$ ($i = 1, 2, 3$) represents the net growth rate of the comprehensive innovation development level of cities in the metropolitan area.

### 3.3. Estimation of Parameters.

To calculate the coefficient of symbiotic effect between core cities and node cities, this study draws on the method of Wu and Wang to estimate the parameters using the gray estimation method [30].

Given that the expansion of (1) is

$$\begin{cases} dx_1/dt = r_1x_1 + r_1u_{12}/N_2x_1x_2 + r_1u_{13}/N_3x_1x_3 \\ dx_2/dt = r_2x_2 - r_2/N_2x_2^2 + r_2u_{21}x_2x_1 + r_2u_{23}/N_3x_2x_3 \\ dx_2/dt = r_3x_3 - r_3/N_3x_3^2 + r_3u_{31}x_3x_1 + r_3u_{32}/N_2x_3x_2 \end{cases}$$

For convenience, (1) is written as follows:

$$\begin{cases} \dfrac{dx_1}{dt} = \alpha_{10}x_1 + \alpha_{11}x_1^2 + \alpha_{12}x_1x_2 + \alpha_{13}x_1x_3, \\ \dfrac{dx_2}{dt} = \alpha_{20}x_2 + \alpha_{22}x_2^2 + \alpha_{21}x_1x_2 + \alpha_{23}x_2x_3, \\ \dfrac{dx_3}{dt} = \alpha_{30}x_3 + \alpha_{33}x_3^2 + \alpha_{31}x_1x_3 + \alpha_{32}x_2x_3. \end{cases} \tag{2}$$

where $\alpha$ is defined as $\alpha_{10} = r_1, \alpha_{11} = 0, \alpha_{12} = r_1u_{12}/N_2, \alpha_{13} = r_1u_{13}/N_3 \alpha_{20} = r_2, \alpha_{22} = -r_2/N_2, \alpha_{21} = r_2u_{21}, \alpha_{23} = r_2u_{23}/\ N_3$ $\alpha_{30} = r_3, \alpha_{33} = -r_3/N_3, \alpha_{31} = r_3u_{31}, \alpha_{32} = r_3u_{32}/N_3$

Based on the mapping relationship between the gray derivative and the even logarithm, the system of equations in equation (2) is discretized to obtain equation (3), as follows:

$$\begin{cases} x_1(t+1) - x_1(t) = \alpha_{10}\dfrac{x_1(t) + x_1(t+1)}{2} + \alpha_{11}\dfrac{[x_1(t) + x_1(t+1)]^2}{4} + \alpha_{12}\dfrac{[x_1(t) + x_1(t+1)][x_2(t) + x_2(t+1)]}{4} + \alpha_{13}\dfrac{[x_1(t) + x_1(t+1)][x_3(t) + x_3(t+1)]}{4}, \\ x_2(t+1) - x_2(t) = \alpha_{20}\dfrac{x_2(t) + x_2(t+1)}{2} + \alpha_{22}\dfrac{[x_2(t) + x_2(t+1)]^2}{4} + \alpha_{21}\dfrac{[x_1(t) + x_1(t+1)][x_2(t) + x_2(t+1)]}{4} + \alpha_{23}\dfrac{[x_2(t) + x_2(t+1)][x_3(t) + x_3(t+1)]}{4}, \\ x_3(t+1) - x_3(t) = \alpha_{30}\dfrac{x_3(t) + x_3(t+1)}{2} + \alpha_{33}\dfrac{[x_3(t) + x_3(t+1)]^2}{4} + \alpha_{31}\dfrac{[x_1(t) + x_1(t+1)][x_3(t) + x_3(t+1)]}{4} + \alpha_{32}\dfrac{[x_2(t) + x_2(t+1)][x_3(t) + x_3(t+1)]}{4} \end{cases} \tag{3}$$

To facilitate the calculation, (3) is transformed into a matrix equation form, as shown in the following:

$$\begin{aligned} X_{1n} &= A_1\alpha_1, \\ X_{2n} &= A_2\alpha_2, \\ X_{3n} &= A_3\alpha_3. \end{aligned} \tag{4}$$

According to the law of least squares, (7) is obtained as follows:

$$\begin{aligned} \widehat{\alpha}_1 &= \left(A_1^T A_1\right)^{-1} A_1^T X_{1n}, \\ \widehat{\alpha}_2 &= \left(A_2^T A_2\right)^{-1} A_2^T X_{2n}, \\ \widehat{\alpha}_3 &= \left(A_3^T A_3\right)^{-1} A_3^T X_{3n}. \end{aligned} \tag{5}$$

Finally, the coefficients are reduced to the system of differential equations to obtain the symbiotic coefficients in the original equations:

$$\begin{aligned} u_{ij} &= \alpha_{ij} \times \frac{N_j}{r_i} \quad (i \neq j, j \neq 1), \\ u_{ij} &= \alpha_{ij} \times \frac{N_j}{r_i} \quad (i \neq j, j = 1). \end{aligned} \tag{6}$$

## 4. Research Object Selection and Index System Construction

*4.1. Research Object Selection.* The promulgation of the "Outline for the Development of Regional Integration in the Yangtze River Delta" in 2019 marks the development path of the Yangtze River Delta toward achieving regional integration and coordinated development. The outline notes that innovation drive is the key to promoting the integrated and high-quality development of the Yangtze River Delta. In the same year, to give full play to the radiation role of core cities and realize the regional agglomeration effect, the National Development and Reform Commission proposed the concept of a metropolitan area in the "Guiding Opinions on Cultivating and Developing Modern Metropolitan Areas." The purpose of the metropolitan area is to consider the megacity as the core, with neighboring node cities participating in the division of labor and cooperation to achieve common development in the areas of finance, culture, innovation, and transport. The latest "Report on the Development of China's Metropolitan Areas" released by Tsinghua University pointed out that the Yangtze River Delta Metropolitan Area is currently the most mature metropolitan area in China, and all its indicators rank first in the country.

As the most important core city in the Yangtze River Delta region, Shanghai plays a crucial role in its integration. The "Outline for the Development of Regional Integration in the Yangtze River Delta" clearly noted that the development of the Yangtze River Delta would promote a regional linkage development with Shanghai as the core. The "Shanghai City Master Plan" also proposed that Shanghai should build a Shanghai metropolitan area that includes Suzhou, Jiaxing, Wuxi, Nantong, and Ningbo, and established an efficient mechanism for cooperation among government, industry, academia, and research in the field of science and technology innovation to share science and innovation resources and form an innovation community. As important node cities adjacent to Shanghai, Suzhou, and Jiaxing are closely related to Shanghai. Suzhou has been known as the "Biluo Spring Tea under the big tree," and for many years, Suzhou has maintained the development concept of harmony but has had Shanghai as the center. In recent years, under the policy of "integrating with Shanghai and promoting integration," Jiaxing and Shanghai have cooperated deeply in terms of industrial platforms, infrastructure, and public services. Specifically, after the "Shanghai-Jiaxing G60 Science and Innovation Corridor Strategy" was proposed, the innovation linkage between the two has become more frequent.

Therefore, by considering Shanghai (core city), Suzhou (node city), and Jiaxing (node city) in the Yangtze River Delta region as the research objects, we were able to fully reflect the current symbiotic relationship and innovation-level development track of the most cutting-edge and mature metropolitan areas in China today.

*4.2. Indicator System Construction and Data Processing.* Comprehensive urban innovation is a development process that involves multiple fields. Most existing studies have measured and evaluated this relationship in terms of knowledge, technology, industry, and environment. In this study, based on the methods of Zhao et al. [31] and Wu and Tan Cui [32], and following the principles of comprehensiveness, scientific quality, and data availability, we constructed an index system from four dimensions: innovation subject, innovation environment, innovation input, and innovation output (as shown in Table 2). Among them, innovation subject is the human foundation of city innovation development; innovation environment provides infrastructure conditions for city innovation development; innovation input is an important guarantee for city innovation development; innovation output is an important criterion to measure the competitiveness of city innovation development and the level of result transformation.

## 5. Empirical Research

*5.1. Calculation of the Comprehensive Innovation Development Level.* At present, the weights for the index system commonly follow the hierarchical analysis method, the Delphi method, the entropy weight method, the principal component analysis method, or the factor analysis method. Considering the fuzziness of the criteria in judging the importance of indicators, we adopted the fuzzy comprehensive evaluation method to determine the weights of the index system of urban innovation development level on the basis of squaring and normalizing the original data. The calculated scores of the city's comprehensive innovation development level are shown in Table 3, and the development trend is shown in Figure 1.

Table 2: Comprehensive innovation development level indicator system.

| Tier 1 indicator | Tier 2 indicators | Tier 3 indicators |
|---|---|---|
| Comprehensive innovation development level | Innovation subject | Number of universities<br>Number of high-tech enterprises<br>Number of scientific research institutions in the city<br>Number of national key laboratories<br>Number of national technology incubators |
| | Innovation environment | CPI<br>GDP per capita in the region<br>Park green area per capita<br>Total number of libraries and museums<br>Number of beds in hospitals and health centers<br>Number of public books per capita |
| | Innovation input | Total expenditures of local government funds for science and technology<br>Total expenditures of local government funds for education<br>R&D investment of industrial enterprises above designated size<br>Number of R&D personnel in industrial enterprises above designated size<br>Number of people engaged in research activities in the university |
| | Innovation output | Number of patent applications<br>Number of patents granted<br>Number of technology market contract transactions<br>Value of technology market contracts<br>Number of national-level science and technology awards<br>Total number of scientific and technical papers published<br>High-tech industry output value |

Table 3: Comprehensive innovation development levels of three cities (2008–2019).

| Year | Shanghai | Suzhou | Jiaxing |
|---|---|---|---|
| 2019 | 0.8522 | 0.5689 | 0.4252 |
| 2018 | 0.7985 | 0.5666 | 0.4246 |
| 2017 | 0.7422 | 0.5588 | 0.4238 |
| 2016 | 0.7025 | 0.5584 | 0.423 |
| 2015 | 0.6528 | 0.5574 | 0.4213 |
| 2014 | 0.6064 | 0.5497 | 0.4179 |
| 2013 | 0.5737 | 0.5372 | 0.4127 |
| 2012 | 0.5324 | 0.5057 | 0.3983 |
| 2011 | 0.5029 | 0.4665 | 0.3669 |
| 2010 | 0.4643 | 0.3915 | 0.325 |
| 2009 | 0.4254 | 0.2995 | 0.2422 |
| 2008 | 0.3911 | 0.2212 | 0.161 |

*5.2. Measurement and Fitting of Coefficient of Urban Symbiosis.* Using the parameter gray estimation method to perform matrix operations on the data in Table 3, the following results can be obtained:

$$\begin{aligned}\alpha_1 &= [\alpha_{10}, \alpha_{11}, \alpha_{12}, \alpha_{13}]^\tau = [0.1014, 0, -0.1655, 0.1305],\\ \alpha_2 &= [\alpha_{20}, \alpha_{22}, \alpha_{21}, \alpha_{23}]^\tau = [0.5319, -2.7433, 0.1203, 2.1858],\\ \alpha_3 &= [\alpha_{30}, \alpha_{33}, \alpha_{31}, \alpha_{32}]^\tau = [0.7859, -1.6879, 0.0335, -0.1678].\end{aligned} \tag{7}$$

Reducing the obtained coefficients to the differential (1), the net growth rates of the innovation development level and symbiotic coefficients for the three subjects are as follows: $r_1 = 0.1014$, $r_2 = 0.5319$, $r_3 = 0.7859$; $u_{12} = -0.3164$, $u_{21} = 0.2262$, $u_{13} = 0.5990$, $u_{31} = 0.0424$, $u_{23} = 1.9131$, $u_{32} = -0.0414$. We concluded that when $u_{12} < 0$, $u_{21} > 0$, Shanghai and Suzhou are in a parasitic symbiotic relationship; when $u_{13} > 0$, $u_{31} > 0$, Shanghai and Jiaxing are in a reciprocal symbiotic relationship; when $u_{23} > 0$, $u_{32} < 0$, Suzhou and Jiaxing are in a parasitic symbiotic relationship. The symbiotic relationships among Shanghai, Suzhou, and Jiaxing in the metropolitan area are shown in Figure 2.

The coefficients derived from the gray estimation are input into Matlab for simulation to observe the evolutionary dynamics of Shanghai, Suzhou, and Jiaxing in terms of their integrated level of urban innovation development, as shown in Figure 3.

According to Figure 3, Shanghai maintained a clear growth trend throughout, whereas Suzhou and Jiaxing followed a faster growth trend in the early stages and leveled off in the later stages. In general, the evolution trend of the comprehensive development level of urban innovation obtained by simulation was consistent with the actual comprehensive development level of urban innovation shown in Figure 1. Thus, it was reasonable and feasible to use the Lotka-Volterra model to study the symbiotic relationship between core cities and node cities in a metropolitan area.

*5.3. Simulation Analysis.* By changing the value of the symbiosis coefficient between the core city and the node city, we could observe the evolution trend of the city's comprehensive innovation development level under different symbiotic relationships. Then, we explored the impact of the symbiotic relationships among the cities on a comprehensive urban innovation development level.

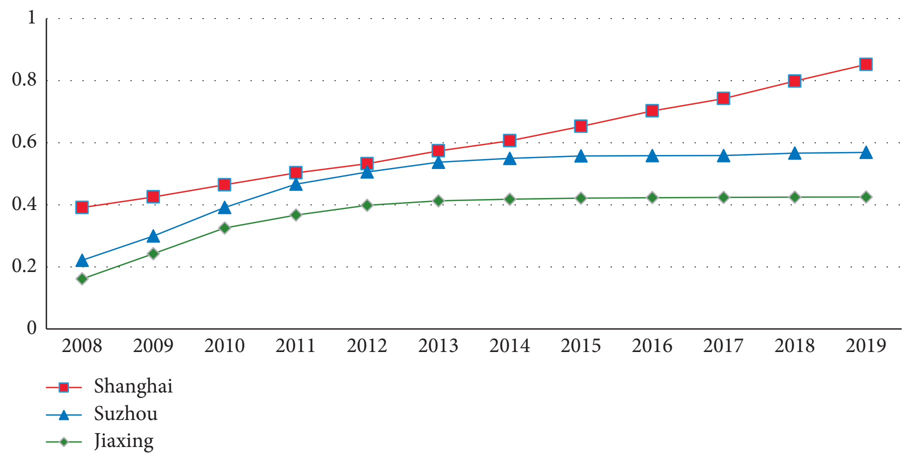


FIGURE 1: Time trend of comprehensive innovation development levels. *Note.* Data are from the China Science and Technology Statistical Yearbook, China Statistical Yearbook, China High and New Technology Industry Statistical Yearbook, Shanghai Statistical Yearbook, Suzhou Statistical Yearbook, Jiaxing Statistical Yearbook, China City Database, WIEGO Statistical Database, websites of Science and Technology Bureau and Statistics Bureau, and government work reports from 2008 to 2019. The descriptive statistics of all indicator data are shown in Table 4.

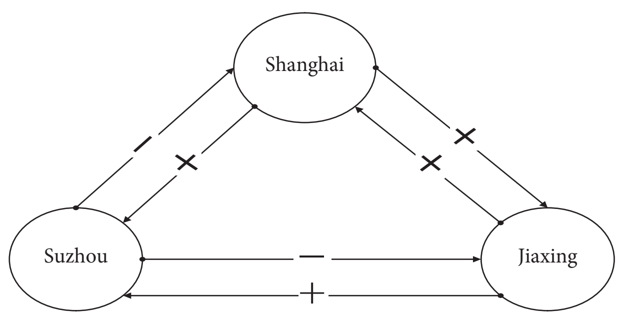


FIGURE 2: Symbiotic relationships among Shanghai, Suzhou, and Jiaxing.

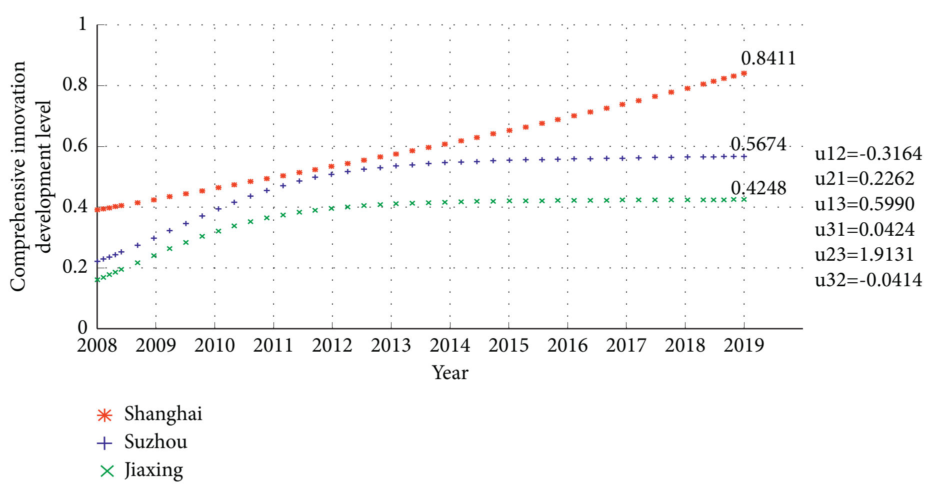


FIGURE 3: Evolution trend of comprehensive innovation development level in Shanghai, Suzhou, and Jiaxing.

*5.3.1. Reciprocal Symbiosis between Core City and Node Cities.* Holding other parameters constant, Figure 4 shows the evolution of the comprehensive innovation development level of the three cities when Shanghai was in a reciprocal symbiotic relationship with Suzhou and Jiaxing. Overall, the level of comprehensive innovation development in all three cities has increased to varying degrees by 2019 compared with the actual situation. The most pronounced rise was in Shanghai, which was in the dominant position in the metropolitan area and had a much higher rate and level of

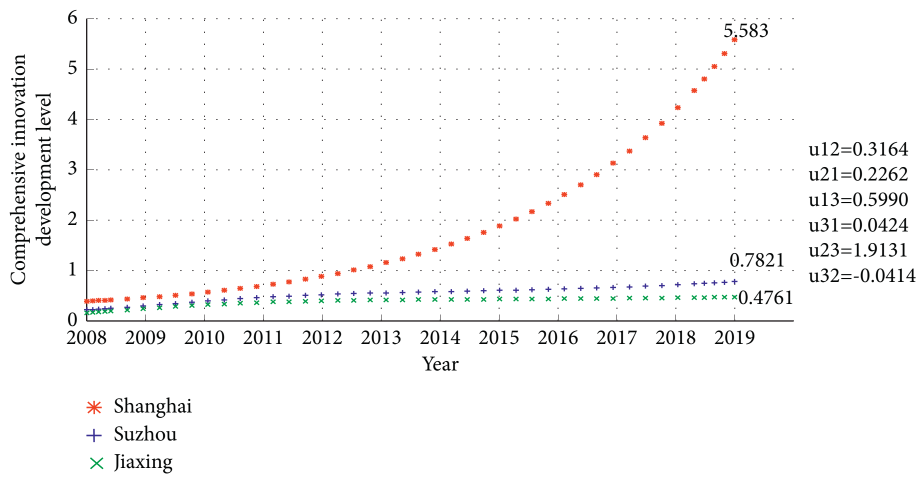


Figure 4: Evolution trend of comprehensive innovation development level under reciprocal symbiosis.

rising than the two node cities. In a metropolitan area, because of the radiation effect of the core cities on the node cities, the level of comprehensive innovation development in the node cities was enhanced, and the innovative development of the node city improved the innovation environment and agglomeration effect of the metropolitan area, which in turn promoted the core city's development. This result suggested that when node cities and core cities maintained a reciprocal symbiotic relationship, the core cities would lead the node cities to achieve a higher level of comprehensive innovation development.

*5.3.2. Mutual Inhibition Symbiosis between Core City and Node Cities.* Holding other parameters constant, Figure 5 shows the evolution of the comprehensive innovation development level of the three cities when Shanghai was in a mutual inhibition symbiotic relationship with Suzhou and Jiaxing. As shown in the graph, the comprehensive innovation development level of the three cities declined compared with the actual level achieved by 2019. Among these cities, the decline in Shanghai was the most evident, and its curve tended to decline slowly after a slight increase. Although Suzhou and Jiaxing have maintained relatively rapid growth, they gradually tended to follow a gradual evolutionary trend, but the final comprehensive development level of innovation was lower than the actual value. Although Suzhou and Jiaxing showed an evolutionary trend of faster growth, followed by a gradual leveling-off, their final comprehensive innovation development was lower than the actual value. In the metropolitan area, because of the relatively high net growth rate of the comprehensive innovation development level of the node cities, it followed an upward trend. Subsequently, because of the dampening effect of the core cities, the growth slowed down and eventually fell below the actual level. The core cities experienced a decline in their comprehensive innovation development because of the combined inhibiting effect of the surrounding node cities. This finding suggested that when the core city and the node city maintained a mutual inhibition symbiotic relationship, the comprehensive innovation development of all three eventually would be lower than the actual level.

*5.3.3. Independent Symbiosis between Core City and Node Cities.* Holding other parameters constant, Figure 6 shows the evolution of the comprehensive innovation development level of the three cities when Shanghai was in an independent symbiotic relationship with Suzhou and Jiaxing. As shown in the graph, by 2019, Shanghai's comprehensive development level of innovation improved significantly compared with the actual situation, whereas Suzhou and Jiaxing had declined to varying degrees. On the one hand, because of the lack of the radiating effect of the core cities, the innovation development of the node cities lost a favorable factor, and thus, the level decreased compared to the actual situation. On the other hand, because of the unconstrained status and inherent advantages of their own resources, the core cities achieved higher levels of innovative development than the actual situation. This finding suggested that when the core city and the node city maintained an independent symbiotic relationship, the comprehensive innovation development of the core cities eventually would be higher than the actual level, and the situation of the node city would be the opposite.

*5.3.4. Parasitic Symbiosis between Core City and Node Cities.* Holding other parameters constant, Figure 7 shows the evolution of the comprehensive innovation development level of the three cities when Shanghai followed a parasitic symbiotic relationship with Suzhou and Jiaxing. As shown in Figure 7, the level of Shanghai's comprehensive innovation development experienced a significant decline. Although Suzhou and Jiaxing maintained a rapid upward trend, followed by a gradual leveling-off, the level of comprehensive innovation development in the two cities was still lower than the actual value in 2019. In the metropolitan area, when node cities were parasitic on core cities, because of the relatively high net growth of comprehensive innovation development level and the innovation spillover of core cities, the

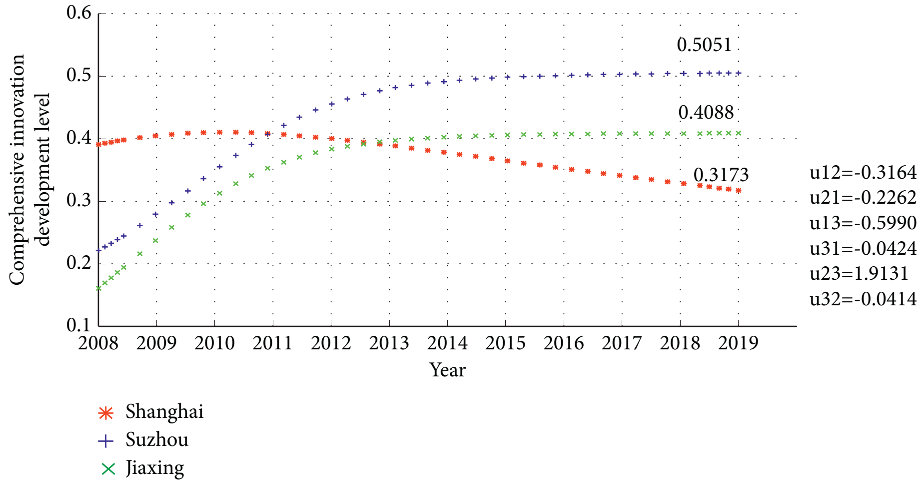


Figure 5: Evolution trend of comprehensive innovation development level under mutual inhibition symbiosis.

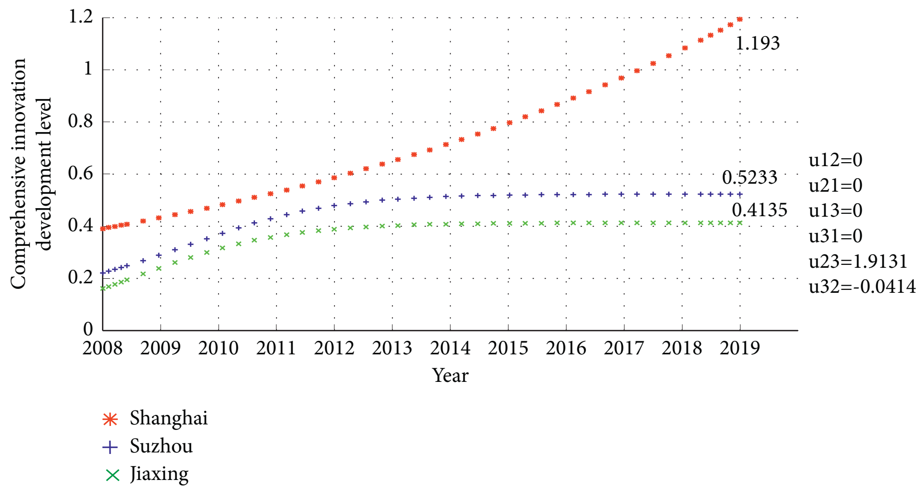


Figure 6: Evolution trend of comprehensive innovation development level under independent symbiosis.

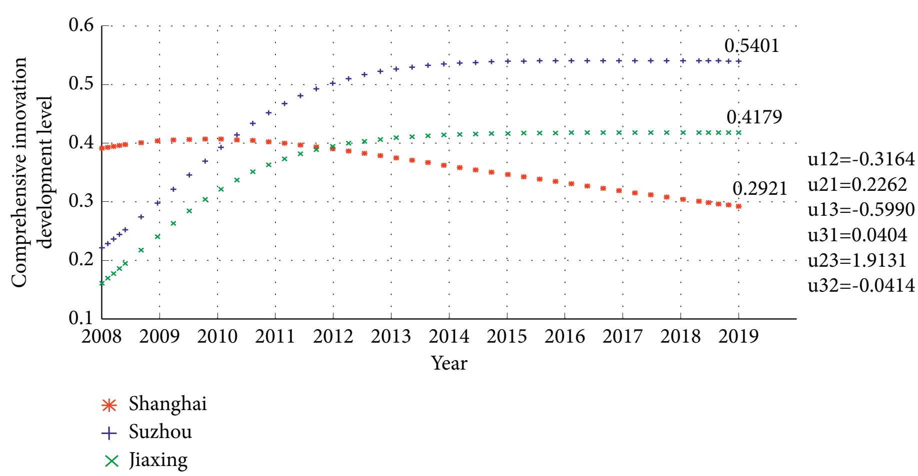


Figure 7: Evolution trend of comprehensive innovation development level under parasitic symbiosis.

Table 4: The descriptive statistics of all indicator data.

| Variable | Obs | Mean | Std. Dev | Min | Max |
|---|---|---|---|---|---|
| Number of universities | 36 | 32.19 | 27.67 | 3 | 97 |
| Number of high-tech enterprises | 36 | 3940 | 2723.97 | 682 | 12619 |
| Number of scientific research institutions in the city | 36 | 75.33 | 60.20 | 3 | 165 |
| Number of national key laboratories | 36 | 12.72 | 13.52 | 0 | 45 |
| Number of national technology incubators | 36 | 18.42 | 16.92 | 0 | 55 |
| CPI | 36 | 102.64 | 1.62 | 98.47 | 105.78 |
| GDP per capita in the region | 36 | 103028 | 34146.17 | 42626 | 162503 |
| Park green area per capita | 36 | 11.38 | 2.89 | 6.97 | 15 |
| Total number of libraries and museums | 36 | 51.33 | 43.62 | 6 | 128 |
| Number of beds in hospitals and health centers | 36 | 63351.97 | 43700.35 | 12484 | 146454 |
| Number of public books per capita | 36 | 1.67 | 1.11 | 0.49 | 3.43 |
| Total expenditures of local government funds for science and technology | 36 | 1079516 | 1336677 | 15911 | 4263655 |
| Total expenditures of local government funds for education | 36 | 2618144 | 3172218 | 88554 | 9956956 |
| R&D investment of industrial enterprises above designated size | 36 | 2364188 | 1641542 | 310289 | 5906504 |
| Number of R&D personnel in industrial enterprises above designated size | 36 | 111702.41 | 168922.8 | 20794 | 812459 |
| Number of people engaged in research activities in the university | 36 | 18672.39 | 18615.67 | 1345 | 69761 |
| Number of patent applications | 36 | 73735.97 | 51495.32 | 5536 | 173586 |
| Number of patents granted | 36 | 54175.72 | 76203.02 | 2984 | 461109 |
| Number of technology market contract transactions | 36 | 16122.33 | 9792.05 | 3708 | 35928 |
| Value of technology market contracts | 36 | 3193590 | 3522234 | 61023 | 14223539 |
| Number of national-level science and technology awards | 36 | 18.03 | 23.94 | 0 | 58 |
| Total number of scientific and technical papers published | 36 | 39139.71 | 27554.14 | 11246 | 97943 |
| High-tech industry output value | 36 | 10222.22 | 10079.98 | 1936.12 | 51239 |

innovative development of node cities followed an upward trend. Because of the continuous reduction of innovation spillovers in core cities, however, the comprehensive innovation development level of node cities ultimately was lower than the actual value. For core cities, because of the inhibiting effect of the two node cities, the level of comprehensive innovation development dropped significantly. This finding suggested that when node cities were parasitic towards core cities, the comprehensive innovation development level would be lower than the actual value.

## 6. Conclusion

From the perspective of symbiosis, this paper combined the development of urban innovation and ecological theory to establish a Lotka-Volterra model that considered core cities and node cities in the metropolitan circle as the research object. On the basis of the construction of an index system for the comprehensive innovation development level of cities, we conducted an empirical study with Shanghai, Suzhou, and Jiaxing as case objects and simulated different symbiotic relationships among core cities and node cities to reveal their evolutionary patterns. The results of this research are as follows:

(1) When the core city and the node city were in a reciprocal symbiotic relationship, the comprehensive innovation development of both was higher than the actual level. In this case, the core cities were in a dominant position and promoted each other with the node cities to form an efficient innovation mechanism. Therefore, in a metropolitan area, the government of the core city should give full play to its leading role in innovation, actively establish cooperation mechanisms with neighboring node cities, develop cooperation channels, and realize the sharing and effective circulation of science and innovation resources by promoting the construction of innovation platforms, such as research centers, laboratories, and information resource centers.

(2) Under the mutual inhibition symbiotic relationship, the innovation development of both core cities and node cities was lower than the actual level. The vicious competition between core cities and node cities inhibited each other, resulting in a wastage of resources and low efficiency of urban innovation development. Therefore, in a metropolitan area, core cities and node cities should break down the barriers of cooperation, avoid vicious competition, and adopt measures such as reciprocal incentives and financial investment to facilitate the transformation of the relationship between them into a reciprocal symbiosis.

(3) Under the independent symbiotic relationship, the comprehensive innovation development level of node cities declined because of the loss of innovation radiation from core cities, whereas core cities still maintained an upward trend because of their natural resources and policy advantages. This difference resulted in the development of innovation in core cities being higher than the actual level and that of node cities being lower than the actual level, forming the "Matthew effect." In a metropolitan area, on the one hand, the governments of the node cities should provide more support to the local innovation industry and prevent the massive outflow of innovation resources [33], such as talents, universities, and

capital, by setting favorable policies and creating a comfortable living environment. On the other hand, they should also proactively develop innovation cooperation with the core cities and expand the radiation effect of the core cities by improving transportation and cobuilding scientific research institutions.

(4) Under the parasitic symbiotic relationship, both core and node cities were below the actual level of innovation development. Because of the massive outflow of innovative resources, the restraining effect between cities, and the reduction of innovation spillovers, the innovative development of both was obviously hindered. Therefore, in a metropolitan area, the node city government should strive to build an innovation system with local characteristics and advantages and enhance internal innovation vitality to reduce excessive innovation dependence on core cities.

## Data Availability

Data are from the China Science and Technology Statistical Yearbook, China Statistical Yearbook, China High and New Technology Industry Statistical Yearbook, Shanghai Statistical Yearbook, Suzhou Statistical Yearbook, Jiaxing Statistical Yearbook, China City Database, WIEGO Statistical Database, websites of Science and Technology Bureau and Statistics Bureau, and government work reports from 2008 to 2019.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

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