Benefits Analysis of Chinese Cities on Urban Networks Based on Evolutionary Games

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Abstract

This paper investigates inter-city cooperation and city benefits based on complex network theory and evolutionary game theory. The games are played on urban networks. First of all, a game payoff matrix with penalty is constructed. Then, according to complex networks theory, using the first, second and third tier cities in China, we construct a BA scale-free network as the initial network. At the end of a round of the games, each city disconnects from uncooperative cities, then randomly selects neighbors of uncooperative cities to connect. And each city chooses a neighbor's strategy as the strategy in the next round with a certain probability. Repeating the game for 20 rounds, we come to the following conclusions. (1) The higher the ranking of cities, the greater the payoffs. The increase of game rounds increases the benefits of second-tier and third-tier cities;(2) After 20 rounds of games, the benefits, strategies and urban networks tend to be stable. The benefits are closely related to the urban networks, but not to the stability strategies of the cities.

Keywords

Evolutionary game, urban networks, the frequency of cooperation, benefits, average degree

1. Introduction

Since 1970s, due to the adjustment of economic structure and the world competition, the competition of cities for limited growth and financial potential has become increasingly fierce. Traditional mandatory coordination imposed by the state and coordination through market exchange are no longer effective ways to solve these problems [1]. Inter-city cooperation is a new policy choice to overcome the negative impact of urban competition [2]. With the deepening of globalization, marketization and decentralization, Chinese cities have also experienced structural adjustment. In recent years, the Chinese government has attached great importance to urban cooperation and regional cooperation, such as the Beijing-Tianjin-Hebei City-region, the Yangtze river delta region and the Guangdong-Hong Kong-Macau Greater Bay Area. Scholars used different regions to study the cooperation between cities [3-5]. Most references study the cooperation in some specific regions, but there are few studies on the cooperation between cities across regions or between all cities in China.

With the rise of research on complex networks, some scholars have analyzed the real world by establishing urban networks [6-9]. Urban networks are the application of network theory to answer theoretical and empirical questions arising from urban research [10]. Camagni [11] and Capello [12] extended the concept of "network externality " [11] originally put forward in economics to "urban network externality". Network externality refers to the fact that cities can increase marginal benefits in complementary relationships and gain additional benefits from cooperation in urban networks [13]. Therefore, the use of city networks allows for a better analysis of the benefits between cities.

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Based on the above analysis, a game model with penalty will be proposed in this paper. Then, a BA scale-free urban network will be constructed. The games will be played on the urban networks. After a round of game, the strategies of each city and urban networks will be updated. The benefits and cooperation behavior of cities and the evolution law of urban networks will be discussed.

2. Model

In the evolutionary game model, the players are the governments of first, second and third tier cities. In this paper, we assume that the players are all finite rational. The games are played on the networks, in which the nodes represent the cities, and the edges represent the game relationship between the cities. If there is a edge between two cities, the two cities play the game once and calculate the benefit P according to the payoff matrix in Table 1.

Table 1
The payoff matrix

		City 2	
		cooperation	uncooperation
City 1	cooperation	$R+0.5R'-C(d)$	$R-C(d)+N-V$
	uncooperation	$R-N+V$	R

In Table 1, R is the payoff from the games played by city 1 and city 2, and R' is all the excess benefit from the cooperation between the two cities. This benefit is equally distributed to both cities. C is the cost of cooperation generated by the cooperation. The cost of cooperation C is related to the distance d between the two cities. The greater the distance, the higher the cooperation cost C. V is the opportunity payoff obtained for the uncooperative city. And N is the default penalty for the uncooperative city. The penalty is directly compensated to the cooperative city.

If there are connected edges between city i and other n_i cities, then city i plays n_i games simultaneously. Sum the payoffs from n_i games to get the total benefit $P_i = \sum_{k=1}^{n_i} p_k$ for city i in that round. By analogy, the total benefit of each city in each round of the game can be obtained. At the end of a round, the city i disconnects from the uncooperative cities and randomly chooses one of the betrayer's neighbors to connect to. In the next round of the game, city i picks its neighbor j's strategy with probability $w_{i \leftarrow j} = 1/\left[1+\exp\left(P_i - P_j\right)\right]$ as its own strategy. The city i chooses a neighbor of the same tier as its own with probability 0.8 as its imitation neighbors, or a neighbor of a different tier than its own with probability 0.2.

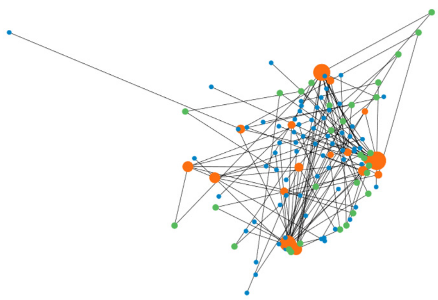

Figure 1: Initial urban network

3. simulation

3.1. Construction of initial urban network

Suppose the urban networks are scale-free networks. In scale-free networks, a few nodes have a large number of connections, while most nodes have few connections. This is in line with the real situation of urban commercial distribution in China. According to the "2022 City Business Attractiveness Ranking List", we classifies first-tier cities and new first-tier cities into first-tier cities, and uses second-tier cities and third-tier cities as the nodes of the urban networks. And we takes the latitude and longitude of cities as coordinates to generate a scale-free network (see Figure 1) as the initial urban network. In Figure 1, the orange, green and blue dots (nodes) represent that the city is the first, second and third tier cities, respectively. The higher the tier of the city, the more connected edges and the larger the dots. It can be seen from Figure 1 that the locations of the first-tier cities and the third-tier cities are relatively uniform, and most of the second- tier cities are located on the edge of China.

3.2. Evolutionary game experiments

Since the cost of cooperation is related to the distance between cities, the distance between cities is calculated based on the latitude and longitude of each city. And it is divided into three categories, $d \le 500$, $500 < d \le 1000$ and $d \ge 1000$, corresponding to the costs $C1$, $C2$ and $C3$ in that order. Let $R=2$, $R'=1$, $C1=0$, $C2=0.5$, $C3=1$, $V=1$ and $N=0.5$. Assume that each city chooses to cooperate with a probability of 0.5 in the first round of the game and plays 20 rounds of the game. The evolutionary game is repeated four times in this paper to prevent accidental results. In this section, red, blue, green and purple are used to represent the four evolutionary games in turn.

The benefits for the 119 cities obtained from the four experiments are depicted in Figure 2. The horizontal coordinates are the 119 cities, and the vertical coordinates from top to bottom shows the 1st to 20th rounds of games. The number on the horizontal coordinates is the tiers corresponding to the 119 cities. The darker the color, the greater the benefit of the city. By observing Figure 2, it can be found that the higher the rank of the city, the greater the benefit. In the previous rounds of the game, the first-tier cities have darker colors and larger benefit, while almost all of the second-tier and third-tier cities have lighter colors and smaller gains. With the increase of game rounds, the color of some second-tier and third-tier cities is obviously deepened, and their benefits are obviously increased. This indicates that the evolutionary game set in this paper can increase the gain of secondary and tertiary cities. And Figure 2 shows that the color of the four experiments gradually lightens, indicating that the cities benefits of these four experiments are smaller.

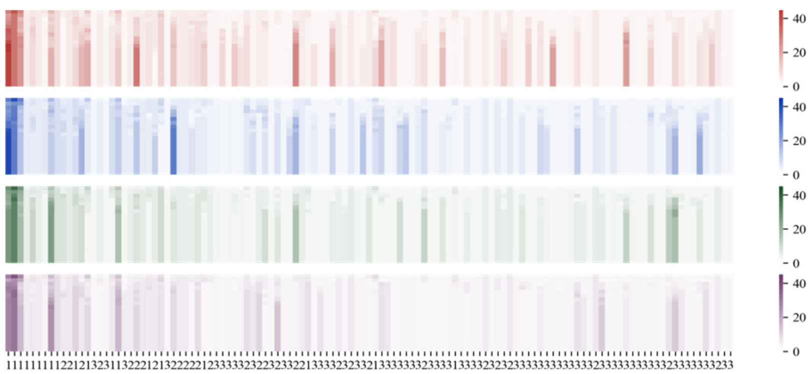

Figure 2: Benefits of 119 cities in 4 experiments

The strategies of the 119 cities in the 4 experiments are depicted in Figure 3. Red, blue, green and purple represent that the strategies of the cities in the 4 experiments are cooperation, and black represents the strategies are uncooperation, respectively. The numbers in the horizontal coordinates are the corresponding tiers of the 119 cities. Figure 3 shows that there are some cities whose strategies are always cooperation or uncooperation in the four experiments. After 20 rounds of the games, the strategies of 119 cities did not change and reached a stable state. In this case, there are 9, 11, 5, and 10 cities' strategies is uncooperation.

Table 2 lists the number of first-, second- and third-tier cities with uncooperative stability strategy in the four experiments. The results in Figure 2 show that the city benefits of the four experiments are becoming smaller. But Table 2 illustrates that the number of cities with uncooperative stability strategy has not remarkablely increased or decreased. This indicates that the correlation between city benefits and the number and tier of cities with uncooperative stabilization strategies is not significant.

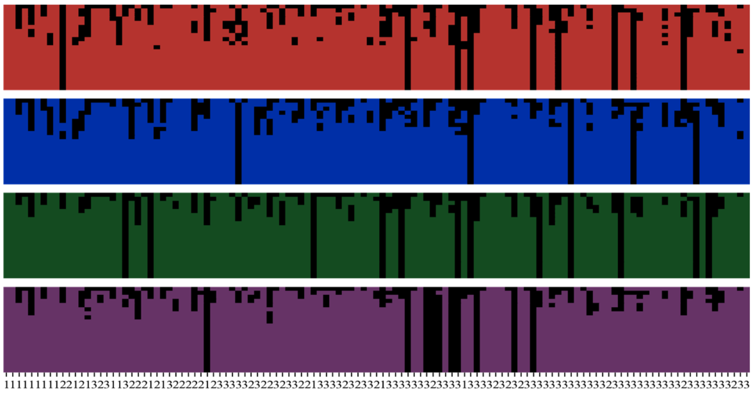

Figure 3: Strategies of 119 cities in 4 experiments

Table 2

The number of cities with uncooperative stability strategy

Experiments	The number of first-tier cities	The number of second-tier cities	The number of third-tier cities
1	0	2	7
2	0	0	5
3	0	0	11
4	1	1	8

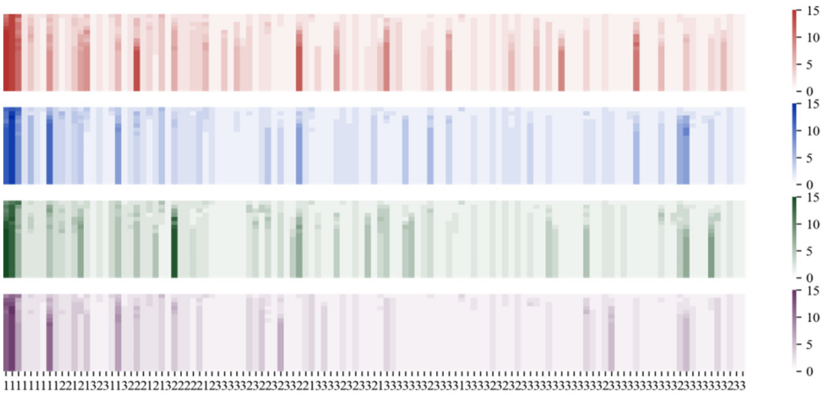

Figure 4: Degree of Urban Network in 4 Experiments

As in Figure 2, Figure 4 depicts the degree of the urban networks in 4 experiments. The darker color indicates the greater degree of that node (city) in that game round, that is, the more cities play with this city. In the previous rounds of games, the color of the first-tier city is darker, while almost all the second-tier and third-tier cities are lighter. As the number of game rounds increased, the colors of some second-tier and third-tier cities has obviously deepened. The evolution results show that the increase of the number of game rounds can make some second-tier and third-tier cities play with many cities in one game round, thus increasing the benefits of second-tier and third-tier cities. It also shows that the colors of the four experiments gradually become lighter, which indicates that the degree of the urban networks is gradually becoming smaller in these four experiments. This is the same as the results shown in Figure 2. It indicates that there is a correlation between the city benefit and the degree of the urban network.

4. Conclusion

Since the 1970s, inter-city cooperation has emerged as a policy to overcome the negative effects of urban competition. In this paper, inter-city cooperation and benefits are studied based on complex network theory and evolutionary game theory. First, this paper constructs a payoff matrix with penalty. Second, a BA scale-free network is built using first-, second-, and third-tier cities in China. The games are played on the networks, where the nodes represent cities and the connected edges represent the game relationships between cities. At the end of a game round, each city disconnects from the betrayer and randomly chooses a neighbor of the betrayer to connect. And the city chooses one of its neighbors' strategy with certain probability as its own strategy in the next game round. Repeating this for 20 rounds, we find that (1) the higher the rank of the city, the greater the benefits. The increase in the number of game rounds increases the benefits of secondary and tertiary cities; (2) some cities' strategies are always cooperation and some cities' strategies are always uncooperation. (3) As the number of rounds of the game increases, the number of cities playing with secondary and tertiary cities also increases; (4) After 20 rounds of the game, the benefits, strategies, and urban networks of cities stabilize. The benefits of cities is strongly related to the urban network, and not much related to the stable strategy of cities.

5. Acknowledgements

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