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Original Paper

An Evolutionary Game Analysis of the Main Body Collaboration of Public-Private Cooperation Projects in Rural Environment

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Abstract

An evolutionary game model was established to study the evolutionary stability strategy of government and social capital in the public-private cooperation model of rural environmental governance and its influencing factors, and to explore the evolution process of cooperative behavior of the main body. The research shows that income distribution, risk distribution, supervision intensity and reward and punishment amount are important factors that affect the choice of cooperative strategy of the main body in the public-private cooperation project of rural environmental governance, and determine the evolution direction of the coordination of the main body behavior. Reducing the cooperative cost, appropriately increasing the risk bearing, and improving the supervision and reward and punishment intensity are conducive to the establishment of the collaborative behavior of the main body in the public-private cooperation model of rural environmental governance.

Keywords

rural area, environmental governance, evolutionary game, synergy

1. Introduction

Rural environmental governance is an important part of the rural revitalization strategy and an inevitable choice to achieve ecological livable. Although the state has vigorously promoted rural environmental governance in recent years, it still faces realistic difficulties such as lack of funds, no maintenance and lack of mechanisms. The problem of rural environmental governance has become a serious challenge to the current agricultural and rural development. At present, the scale, structure and effect of investment in rural environmental governance are still difficult to meet the demand, rural garbage collection and treatment facilities, sewage treatment facilities and so on lag behind seriously

compared with the city, rural livability needs to be improved, these factors restrict and affect China's rural economic development and the improvement of farmers' quality of life. To this end, the No. 1 document of the central Committee has repeatedly pointed out that the construction should focus on rural areas, guide social capital to invest in agriculture and rural areas, and continuously improve rural living environment.

There is still a big gap between rural environmental governance facilities and urban ones, and the management mechanism is not yet perfect, which is far from meeting the requirements of ecological livable and sustainable development. The public-private partnership projects in rural areas are characterized by strong public welfare, long payback period, low rate of return and many uncertain factors, and are faced with relatively complex situations. Scholars generally believe that the current public-private partnership model has improved the investment efficiency, but there are some problems in the process of rural environmental governance, such as ineffective application, low operational efficiency and weak enthusiasm of private sector participation. Take a rural solid waste treatment public-private cooperation project as an example. In this project, in order to obtain higher returns, social capital will first build projects with high profits, and then carry out rural environmental governance, focusing on low-cost projects with high returns such as urban infrastructure construction, land consolidation, park construction, etc. For rural environmental governance, it is necessary to delay or deal with inspections if possible. It can be seen that in order to improve output efficiency and resolve the contradictions between stakeholders, it is necessary to build a public-private cooperation interest coordination mechanism to reduce risks, ensure transaction safety and reasonable returns. In view of this, this paper will focus on the selection mechanism of subject behavior coordination in the public-private cooperation project of rural environmental governance, build a two-population game model of evolutionary game, and study the optimization strategy of behavior coordination, which has important theoretical and practical significance for improving the supply efficiency of public-private cooperation model of rural environmental governance.

2. Construction and Analysis of Game Model

2.1 Problem Description and Hypothesis

The establishment of benign public-private partnership is the key to ensure the operation of public-private partnership projects in rural environmental governance, and the cooperation between the government and social capital is the ideal state of the partnership. The main body behavior coordination in the rural environmental governance public-private cooperation project refers to the process in which the government and social capital participating in the rural environmental governance public-private cooperation project cooperate with each other in the cooperation process, actively implement the cooperation agreement, and jointly promote the efficient construction and good operation of the rural environmental governance public-private cooperation project, including the following meanings: (1) The government side and the social capital side strictly fulfill their obligations and assume

responsibilities in accordance with the rural environmental governance public-private partnership contract, maintain good communication and exchange, and maintain coordination at the cooperation level, so as to ensure the quality of the rural environmental governance public-private partnership project. (2) In the process of coordination, the behaviors of all parties influence and interact with each other, and the two parties actively cooperate to ensure the good operation of rural environmental governance projects.

Based on the existing research results, the following assumptions are made:

Hypothesis 1: Both parties are bounded rational players, and the government side and the social capital side have two kinds of strategy choices, the strategy set is (synergistic, non-synergistic). One party will choose and adjust its own strategy according to the other party's strategy. The total return of the government side and the social capital side is V_a and V_p respectively. V_a includes not only the economic return, but also the improvement of rural living environment and the improvement of agricultural production efficiency caused by the improvement of rural environmental governance. The cooperation between the government side and the social capital side will pay the necessary costs, including information search, communication, implementation of agreements, strict management, risk prevention, etc. The government side's synergy cost is C_a, and the social capital side's synergy cost is C_p.

Suppose 2 that the quality of public-private cooperation project is improved and the risk is reduced by the cooperative behavior of the main body, and it is rewarded by the superior department in material and political terms and benefits in terms of reputation. The reward is set as R, where the proportion allocated to the government side is α, and the proportion allocated to the social capital side is 1-α($0<\alpha<1$), α is the profit distribution coefficient. The non-cooperative behavior of any party due to the pursuit of private interests will affect the overall quality and efficiency of the PPP project to varying degrees. The party without coordination will bear the project loss, and the income will decrease accordingly. The loss assumption coefficient is $\delta(0<\delta<1)$.

Hypothesis 3: In order to pursue utility maximization, both parties are likely to have opportunistic behaviors and adopt non-cooperative strategies. Assume that the government side will get G_a by adopting non-cooperative strategies, and the social capital side will get G_p by adopting non-cooperative strategies.

Assume 4 that both parties adopt non-collaborative strategies, which will lead to the failure of normal operation of the public-private partnership project. When external supervision finds out the implementation of non-collaborative strategies, corresponding penalties will be imposed, including fines, disqualification, blacklisting, etc. The penalty is set as L. According to the principle of relative benefit and risk sharing, the punishment ratio of the government side and the social capital side is α and 1-α respectively. And the probability of being discovered by external supervision is p. And assume that $pL<R$. This article assumes that all symbol values are greater than zero.

2.2 Model Construction

Based on the above parameter assumptions, the payment matrix of the cooperative game between the government and social capital in the public-private cooperation project of rural environmental governance is constructed, as shown in Table 1.

Table 1. Payment Matrix of the Main Body Game in the Rural Environmental Governance Public-Private Cooperation Project

Social capital side	Government side	
	cooperative (y)	non-cooperative $(1-y)$
cooperative (x)	V_p-C_p $+(1-\alpha)R$, V_a-C_a $+\alpha R$	$V_p - C_p$, $(1-\delta)V_a + G_a$
non-cooperative $(1-x)$	$(1-\delta)V_p+G_p$, $V_a - C_a$	$(1-\delta)V_p$-p$(1-\alpha)L+G_p$, $(1-\delta)V_a$-p$\alpha L+G_a$

Suppose the probability that the social capital side of the project adopts the collaborative strategy is x, and the probability that the government side adopts the collaborative strategy is y, then the expected return of the social capital side adopting the collaborative strategy is:

$$U_1 = y\left[V_p - C_p + (1-\alpha)R\right] + (1-y)[V_p - C_p] \tag{1}$$

The expected benefits of the non-cooperative strategy adopted by the social capital side of the project are:

$$U_2 = y[(1-\delta)V_p + G_p] + (1-y)[(1-\delta)V_p - p(1-\alpha)L + G_p] \tag{2}$$

The average expected return of the social capital side of the project is:

$$\bar{U}_{12} = xU_1 + (1-x)U_2 \tag{3}$$

The replication dynamic equation of the collaborative strategy adopted by the social capital side of the project can be obtained as follows:

$$F(x) = \frac{dx}{dt} = x(1-x)\left[(1-\alpha)(R - pL)y + \delta V_p - C_p - G_p + p(1-\alpha)L\right] \tag{4}$$

The expected benefits of the government's collaborative strategy are as follows:

$$U_3 = x(V_a - C_a + \alpha R) + (1-x)(V_a - C_a) \tag{5}$$

The expected benefits of the non-cooperative strategy adopted by the government side are:

$$U_4 = x\left[(1-\alpha\delta)V_a + G_a\right] + (1-x)\left[(1-\delta)V_a - p\alpha L + G_a\right] \tag{6}$$

The average expected return of the government side is:

$$\bar{U}_{34} = yU_3 + (1-y)U_4 \tag{7}$$

Then the replication dynamic equation for the government to adopt the cooperative strategy is as follows:

$$F(y) = \frac{dy}{dt} = y(1-y)[(\alpha R - p\alpha L)x + \delta V_a - C_a - G_a + p\alpha L] \tag{8}$$

Can get the government side and social capital side of the replication dynamic system:

$$\begin{cases} \dfrac{dx}{dt} = x(1-x)\left[(1-\alpha)(R-\mathrm{p}L)y + \delta \mathrm{V}\mathrm{p} - C_p - G_p + \mathrm{p}(1-\alpha)L\right] \\ \dfrac{dy}{dt} = y(1-y)[(\alpha R - \mathrm{p}\alpha L)x + \delta \mathrm{V}\mathrm{a} - C_a - G_\mathrm{a} + \mathrm{p}\alpha L] \end{cases} \tag{9}$$

Let F(x) = 0, F(y) = 0 to get the five equilibrium points of the replicated dynamic system, namely O(0, 0), A(1,0), B(1,1), C(0, 1), D(x*, y*), where:

$$x^* = \frac{\delta \mathrm{V}_\mathrm{a} + \mathrm{p}\alpha L - C_a - G_\mathrm{a}}{\mathrm{p}\alpha L - \alpha R} \tag{10}$$

$$y^* = \frac{\delta \mathrm{V}_\mathrm{p} + \mathrm{p}(1-\alpha)L - C_p - G_p}{(1-\alpha)(\mathrm{p}L - R)} \tag{11}$$

The partial derivative of the replication dynamic equation in the system is obtained respectively, then the Jacobian matrix is:

$$J = \begin{pmatrix} (1-2x)\left[(1-\alpha)(R-\mathrm{p}L)y + \delta \mathrm{V}_\mathrm{p} - C_p - G_p + \mathrm{p}(1-\alpha)L\right] & x(1-x)(1-\alpha)(R-\mathrm{p}L) \\ y(1-y)(\alpha R - \mathrm{p}\alpha L) & (1-2y)[(\alpha R - \mathrm{p}\alpha L)x + \delta \mathrm{V}_\mathrm{a} - C_a - G_\mathrm{a} + \mathrm{p}\alpha L] \end{pmatrix}$$

The determinant of the matrix J is:

$$\det J = (1-2x)\left[(1-\alpha)(R-\mathrm{p}L)y + \delta \mathrm{V}_\mathrm{p} - C_p - G_p + \mathrm{p}(1-\alpha)L\right](1-2y)[(\alpha h - \mathrm{p}\alpha L)x + \delta \mathrm{V}_\mathrm{a} - C_a - G_\mathrm{a} + \mathrm{p}\alpha L]$$
$$-x(1-x)y(1-y)\alpha(1-\alpha)(R-\mathrm{p}L)^2$$

The trace of matrix J is:

$$trJ = (1-2x)\left[(1-\alpha)(R-\mathrm{p}L)y + \delta \mathrm{V}_\mathrm{p} - C_p - G_p + \mathrm{p}(1-\alpha)L\right]$$
$$+(1-2y)[(\alpha R - \mathrm{p}\alpha L)x + \delta \mathrm{V}_\mathrm{a} - C_a - G_\mathrm{a} + \mathrm{p}\alpha L]$$

2.3 Strategy Discussion

For simple analysis, Ling represents the difference between the value function of the government side's cooperation and the value function of the government side's non-cooperation when the social capital side of the project chooses not to cooperate, that is, the relative net payment of the government side's choice of collaborative strategy; $\pi_1 = \delta \mathrm{V}_\mathrm{a} + \mathrm{p}\alpha L - C_a - G_\mathrm{a}$ Ling, denotes the difference between the synergistic value function of the social capital side and the non-synergistic value function when the government side chooses no synergistic strategy, that is, the relative net payment of the social capital side choosing the synergistic strategy; $\pi_2 = \delta \mathrm{V}_\mathrm{p} + \mathrm{p}(1-\alpha)L - C_p - G_p$ $\pi_3 = \delta \mathrm{V}_\mathrm{p} + (1-\alpha)R - C_p - G_p$, represents the difference between the synergistic value function of the social capital side and the non-synergistic value function when the government side adopts the synergistic strategy; $\pi_4 = \alpha R + \delta \mathrm{V}_\mathrm{a} - C_a - G_\mathrm{a}$ Represents the difference between the synergistic value function of the government and the non-synergistic value function of the social capital when the government adopts the synergistic strategy.

According to evolutionary game theory, the equilibrium point satisfying detJ>0 and trJ<0 is the evolutionarily stable point of the system, so the following analysis is carried out.

Table 2. Judgment Table of Evolutionary Game Equilibrium

Equilibrium Points	detJ	trJ
(0,0)	PI_1 PI.	PI_1 + PI.
(0,1)	- PI_1 PI	PI_3 PI -
(1,0)	- PI_2 PI	PI_4 PI -
(1,1)	PI_3 PI.	- PI_3 - PI
(x*, y*)	$\frac{-\pi_1\pi_2\pi_3\pi_4}{(\pi_4-\pi_1)(\pi_3-\pi_2)}$	0

Suppose R>pL, see $\pi_1<\pi_4$，$\pi_2<\pi_3$, and various combinations of the four expressions yield a total of nine different cases.

According to the stability analysis results of each equilibrium point, the following strategy analysis is made:

Case 1: when $\pi_1<0$、$\pi_2<0$、$\pi_3<0$、$\pi_4<0$, point (0, 0) is the evolution-stable point (ESS). Regardless of the strategy chosen by the social capital side of the project, the relative net payment of the government side adopting the synergy strategy will always be negative, so the government side will tend to choose no synergy, regardless of the strategy chosen by the government side, the relative net payment of the social capital side choosing synergy will always be negative, so the social capital side tends to prefer the non-synergy strategy, and the evolutionally-stable strategy is (no synergy, no synergy).

Case 2: when $\pi_1<0$、$\pi_2<0$、$\pi_3<0$、$\pi_4>0$, the point (0, 0) is the evolutionarily stable point (ESS). No matter what strategy the government chooses, the relative net payment of the project social capital side choosing synergy will always be negative, so the social capital side will tend to prefer the non-cooperative strategy. In this case, the relative net payment of the government side adopting synergy strategy will always be negative, so the government side will tend to choose the non-cooperative strategy, and the evolutionary stability strategy is (no synergy, no synergy).

Case 3: when $\pi_1<0$、$\pi_2<0$、$\pi_3>0$、$\pi_4<0$, the point (0, 0) is the evolutionarily stable point (ESS). Regardless of the strategy chosen by the social capital side, the relative net payment of the government side adopting the synergistic strategy is always negative, so the government side will tend to choose the non-synergistic strategy, and the social capital side will always choose the relative net payment of the social capital side choosing the synergistic strategy is negative, so the social capital side will tend to choose the non-synergistic strategy, and the evolutionarily stable strategy is (no synergy, no synergy).

Case 4: When $\pi_1<0$、$\pi_2<0$、$\pi_3>0$、$\pi_4>0$, the points (0, 0), (1,1) are evolutionarily stable points (ESS). The long-term equilibrium result of the game between the government side and the social capital side may be (synergistic, synergistic) or (non-synergistic, non-synergistic), and the strategies adopted by the two sides will be determined according to the strategic choice of the other side. The active cooperation between the government side and the social capital side will enable the rural environmental governance project to achieve a higher operation effect, so a reasonable contract and behavioral constraint

framework will be established. It is helpful to adjust the behavioral preferences and income expectations of all parties, so as to enhance the tendency of synergy and promote the evolution of the game towards (synergy, synergy).

Case 5: when $\pi_1>0$、$\pi_2<0$、$\pi_3<0$、$\pi_4>0$, point C (0, 1) is the evolution-stable point (ESS). On the social capital side, no matter which strategy the government chooses, the relative net payment of the social capital side choosing synergy is always negative, so it will tend to choose the non-cooperative strategy to maximize its own interests; Since the relative net payment of the government side choosing synergy is positive when the social capital side chooses no synergy, the government side will tend to choose the synergy strategy, and the evolutionarily stable strategy is (no synergy, synergy).

Case 6: when $\pi_1<0$、$\pi_2>0$、$\pi_3>0$、$\pi_4<0$, point A (1,0) is the evolutionarily stable point (ESS). On the social capital side, no matter which strategy the government chooses, the relative net payment of the social capital side choosing synergy will always be positive, so the social capital side will tend to choose synergy strategy, no matter how the social capital side chooses, the relative net payment of the government side adopting synergy strategy will always be negative, so the government side will tend to choose no synergy, the evolutionarily stable strategy is (synergy, (no synergy).

Case 7: Point B (1,21) is an evolutionarily stable point (ESS) when $\pi_1>0$、$\pi_2<0$、$\pi_3>0$、$\pi_4>0$.

No matter how the social capital chooses, the relative net payment of the government side adopting the synergy strategy is always positive, so the government side will tend to cooperate, and the relative net payment of the social capital side choosing the synergy strategy is always positive, so the social capital side will tend to choose the synergy strategy, and the evolutionarily stable strategy is (synergy, synergy).

Case 8: when $\pi_1<0$、$\pi_2>0$、$\pi_3>0$、$\pi_4>0$, point B (1,1) is the evolutionarily stable point (ESS).

On the social capital side, no matter which strategy the government chooses, the relative net payment of the social capital side choosing synergy is always positive, so the social capital side will tend to choose the synergy strategy. In this case, the relative net payment of the government side adopting the synergy strategy is always positive, so the government side will tend to choose synergy, and the evolutionarily stable strategy is (synergy, synergy).

Case 9: when $\pi_1>0$、$\pi_2>0$、$\pi_3>0$、$\pi_4>0$, point B (1,1) is the evolutionarily stable point (ESS).

No matter what strategy the government chooses, the benefits of the social capital side implementing the active operation strategy are greater than the benefits of the negative operation strategy, that is, the relative net payment of the choice of synergy is always positive, so the social capital side will prefer the synergy strategy; According to the principle of benefit maximization, no matter what strategy the social capital chooses, the relative net payment of the government side choosing synergy will always be positive, so the government side will tend to choose synergy strategy, and the evolutionarily stable strategy is (synergy, synergy).

Through the analysis of strategy choices in different situations, it can be seen that the strategy choice of game players depends on the relative net payment of synergistic and non-synergistic strategies. Various

influencing factors in the game process affect the relative net payment of synergistic and non-synergistic strategies, and then affect the strategy choice of game players to improve the relative net payment of synergistic strategies. Can promote the government side and social capital side to choose synergistic strategy. The game between the government and social capital involves nine possible scenarios. The influencing factors of the government side's strategy choice include total revenue V_a, cooperative cost C_a, reward R, income G_a of non-cooperative strategy, distribution ratio α, probability p of being discovered by supervision, and penalty L. When other parameters remain unchanged, the government side will be prompted to choose cooperative strategy by improving the income brought by the cooperative behavior of the main body, increasing the intensity of supervision, increasing the intensity of punishment, and reducing the cooperative cost. The factors influencing the strategy choice of the social capital side include total income V_p, synergy cost C_p, reward R, non-synergy strategy income G_p, distribution proportion α, probability p of regulatory discovery and penalty L. When other parameters remain unchanged, increase the distribution income of principal behavior synergy, increase the probability of regulatory discovery, increase the intensity of punishment and reduce the performance cost of the social capital side. Will encourage the social capital side to choose the synergy strategy. In other words, the strategy choice of the government side and the social capital side depends on the relative net payment of the strategy. Various factors affect the relative net payment of different strategies, and then affect the strategic choice of the game players. Therefore, improving the relative net payment of the cooperative strategy can promote the social capital side to adopt the cooperative strategy.

3. Simulation Analysis

Using Matlab for example analysis, simulate the evolutionarily stable strategy of the cooperative game between the government side and the social capital side when the risk bearing coefficient δ, reward R, probability p found by external supervision and penalty limit L take different values. It is assumed that both the social capital side and the government side have a probability of 0.5 to choose different behavioral decisions, and the time step is set as 0.01, α=0.2, Vp=80, Cp=20, Gp=10, Va=20, Ca=2, Ga=2.

3.1 The Influence of Adjusting Risk Bearing Coefficient on System Evolution

Simulate the evolutionary paths of the two parties when δ values are 0.1, 0.5 and 0.9 (set p=1, R=100, L=100), as shown in the figure below, it can be found that when δ values are 0.1, 0.5 and 0.9 respectively, the government side and the social capital side tend to the collaborative strategy in the end, and when δ values are larger, The convergence speed of the government side and the social capital side is faster, indicating that increasing the risk bearing coefficient will help the game between the government side and the social capital side to evolve into the coordinated behavior of the main body.

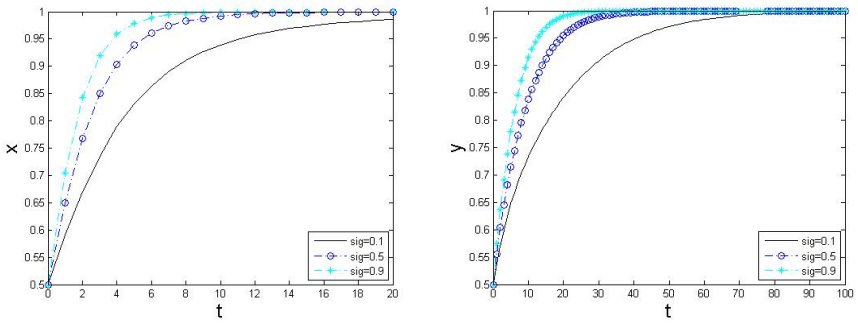

Figure 1. System Evolution Trajectory When δ Value Changes

3.2 Effects of Adjusting Reward Intensity on System Evolution

Simulate the evolution path of the government and social capital when R is 20, 60 and 80 (set δ=0.4, p=1, L=100), as shown in the figure below, it can be found that incentive measures promote the cooperative behavior of the government and social capital, and the greater the value of R, the faster the convergence rate of the government and social capital. This indicates that increasing the incentive intensity helps the game between the government and social capital to evolve into the coordinated behavior of the main body.

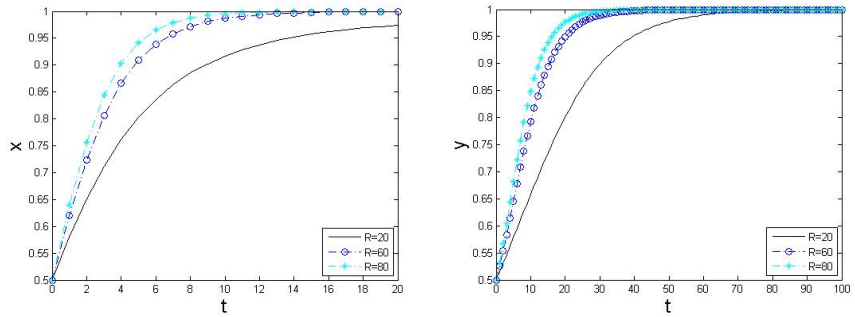

Figure 2. System Evolution Trajectory when R Value Changes

3.3 Influence of Adjusting Penalty Intensity on System Evolution

By simulating the evolutionary paths of both sides when L is 10, 40 and 80 (set δ=0.4, p=1, R=100), as shown in the figure below, it can be found that when L is 10, 40 and 80, both the government side and the social capital side eventually tend to the (cooperative, cooperative) strategy, and with the increase of penalty intensity, the speed of the cooperative strategy tends to be faster. This indicates that increasing the punishment intensity helps the game between the government and social capital to evolve into the coordination of the main body behavior.

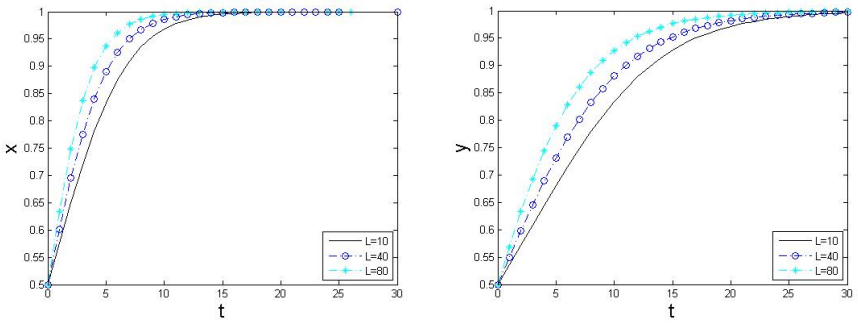

Figure 3. System Evolution Trajectory when L Value Changes

3.4 Effects of Adjusting Regulatory Intensity on System Evolution

Simulate the evolution paths of both parties when p values are 0.1, 0.5 and 0.9 (set δ=0.4, R=100, L=100), as shown in the figure below. It can be found that when p values are 0.1, 0.5 and 0.9, both the government side and the social capital side tend to the (cooperative, cooperative) strategy in the end, but when p values are larger, The faster they tend to cooperate, indicating that external supervision promotes cooperative behavior, and with the strengthening of external supervision, the evolution speed of cooperative behavior selection by both parties is accelerating.

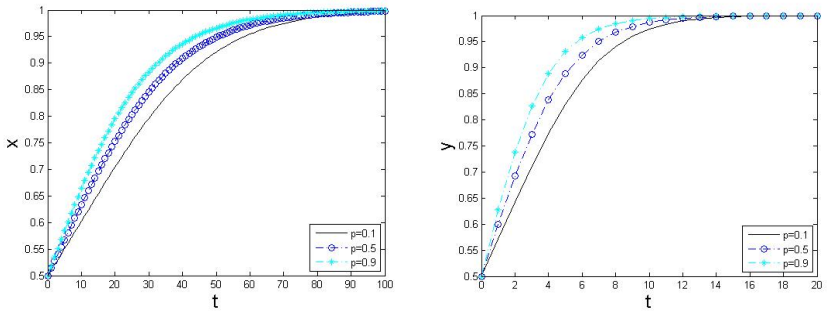

Figure 4. System Evolution Trajectory When P Value Changes

4. Conclusion

This paper establishes an evolutionary game model of the cooperative behavior between the government and the social capital in the rural environmental governance public-private cooperation project, and analyzes the evolutionary stability strategy of both sides. The research shows that increasing the relative net payment of the collaborative strategy can promote the government and social capital to choose the collaborative strategy; Appropriately increasing risk taking and improving incentive level within a reasonable range are conducive to promoting the coordination of subject behavior. Incentive measures such as assessment and incentive, exploring profit points and assisting financing can be adopted to promote the coordination of subject behavior. Increasing punishment and improving external supervision can promote the coordination of main body behavior between the

government and social capital in the public-private cooperation projects of rural environmental governance.

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