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Research on Evolutionary Game of Carbon Emission Reduction Between Government and Enterprise Based on System Dynamics

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Abstract: In order to explore the game relationship between government and enterprises in carbon emission reduction, this article analyzes the costs and benefits under different strategies of government and enterprises. The evolutionary game model of government and enterprise is constructed by using the method of system dynamics. The evolution path of the behavior of both government and enterprise is described in detail through simulation calculation, and the influence of system parameters and initial values on the evolution result is analyzed. The results show that the increase of emission reduction subsidy and fine is conducive to to improving the enthusiasm of government and enterprise behavior. To some extent, the increase of initial behavior probability of government and enterprise will have a positive impact on the evolutionary stability results. However, the government and enterprise can not reach the optimal state(regulation, take). How to improve this state is the future research direction.

Keywords: Carbon emission reduction; Evolutionary game; System dynamics; Dynamic strategy

1 Introduction

Carbon dioxide emissions caused by fossil energy consumption and climate change have become a major global issue. Many global problems, such as frequent natural disasters, fragile ecosystem and rising sea level, not only have a serious impact on human economic life, but also pose a huge threat to human survival and development [1]. More importantly, global climate change is most likely caused by human activities. Therefore, reducing carbon emissions has become an objective need for human survival and development. Government and enterprises are two important subjects in carbon emission reduction. Correctly handling conflicts and cooperation between local governments and enterprises on emission reduction is the key to achieving a low-carbon economy [2].

Academia has done a lot of research on the relationship between government policy and enterprise emission reduction behavior. The interaction between government and manufacturer is described as Stackelberg game. Applying the stylized model can deduce the equilibrium strategy of government and manufacturer [3]. Based on Stackelberg game, a social welfare model considering carbon emission is constructed [4], and it is concluded that block carbon tax is more conducive to encourage low-carbon production. A two-stage dynamic game model [5] was used to study the influence of government subsidy strategies on government-enterprise game relationship and enterprise decision-making. As a relatively new model, the dynamic time-sharing game model effectively explains the impact of government decision-making on the

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temporal characteristics of enterprise low-carbon technological innovation systems [6].

Most of the above literatures are based on a series of classical game models. The rational basis of classical game theory adopts a "complete rationality" hypothesis, which requires a higher degree of rationality than the assumption of "rational economic man" based on "individual rationality" in neoclassical economics [7]. However, there are always systematic reasoning errors in the economic decision-making of game players, and most of these errors are caused by factors such as information cost, thinking cost, excitement and experience [8]. At this time, evolutionary games based on bounded rationality [9] with the characteristics of continuous learning and continuous adjustment are more practical [10]. Based on the bounded rationality of game subjects, this paper constructs the evolutionary game model between government and enterprise. The system dynamics method is used to analyze the interaction mechanism between the two, and the evolution path is further described through simulation experiments.

2 Evolutionary Game Analysis of Government and Enterprise

The two players of the game are local government and enterprises. Enterprises can take carbon emission reduction measures or not. The comprehensive income of enterprises after taking carbon emission reduction measures is E_1, the cost of taking carbon emission reduction measures is P_c,and the income of not taking carbon emission reduction measures is E_2. The government has two choices for the emission reduction of enterprises: Regulation and non Regulation. The government's social benefits are G_1 when the enterprise takes carbon emission reduction measures, and G_2 when the enterprise does not take carbon emission reduction measures. Under the condition of government regulation,the government will give subsidy B when the enterprise takes measures, and charge a fine R when the enterprise does not take measures. The government's expenditure for formulating carbon emission reduction policies, regulating enterprises, etc. is set as P_g. It is assumed that the government will not generate additional benefits and costs without regulation, and the above parameters are all greater than zero. The game payment matrix of government and enterprise is shown in Table 1.

Table 1: Game pay-off matrix between enterprise and government

		The enterprise	
		Take(y)	Not take(1-y)
Government	Regulation(x)	(G_1-P_g-B,E_1-P_c+B)	(G_2-P_g+R,E_2-R)
	Non regulation($1-x$)	(G_1,E_1-P_c)	(G_2,E_2)

Assuming that the probability of enterprises taking carbon emission reduction measures is y,the probability of not taking is 1-y;the probability of government regulation is x, and the probability of non-regulation is 1-x. Suppose that the expected return of the government adopting the regulation strategy is S_{11},and the expected return of the government adopting the non regulation strategy is S_{12}.According to the pay-off matrix, the expected return of government's choice of regulation and non regulation are respectively:

$$S_{11} = y(G_1 - P_g - B) + (1 - y)(G_2 - P_g + R) \tag{1}$$

$$S_{12} = yG_1 + (1 - y)G_2 \tag{2}$$

From Eq. (1) and Eq. (2), the average expected return of the government is:

$$\overline{S_1} = xS_{11} + (1 - x)S_{12} \tag{3}$$

According to Eq. (1), (2), and (3), the replication dynamic equation of government behavior can be constructed as follows

$$F(x) = dx/dt = x(S_{11} - \overline{S_1}) = x(1 - x)[R - P_g - y(B + R)] \tag{4}$$

Suppose that the expected return of the company taking carbon emission reduction measures is S_{21}, and the expected return of not taking the carbon emission reduction measures is S_{22}.According to the pay-off matrix, the expected return of enterprises taking and not taking carbon emission reduction measures are respectively:

$$S_{21} = x(E_1 - P_c - B) + (1 - x)(E_1 - P_c) \tag{5}$$

$$S_{22} = x(E_2 - R) + (1 - x)E_2 \tag{6}$$

From Eq. (5) and Eq. (6), the average expected return of the enterprise is:

$$\overline{S_2} = yS_{11} + (1 - y)S_{22} \tag{7}$$

According to Eq. (5), (6) and (7), the replication dynamic equation of enterprise behavior is constructed as follows:

$$F(y) = dy/dt = y(S_{21} - \overline{S_2}) = y(1 - y)[E_1 - P_c - E_2 + x(B + R)] \tag{8}$$

Thus, a two-dimensional dynamic system can be formed:

$$\begin{cases} F(x) = dx/dt = x(S_{11} - \overline{S_1}) = x(1 - x)[R - P_g - y(B + R)] \\ F(y) = dy/dt = y(S_{21} - \overline{S_2}) = y(1 - y)[E_1 - P_c - E_2 + x(B + R)] \end{cases} \tag{9}$$

Let Eq. (4) and (8) be equal to zero, and obtain two sets of steady state solutions: $x_1 = 0$,$x_2 = 1$,$y^* = \frac{R-P_g}{B+R}$;$y_1 = 0$,$y_2 = 1$,$x^* = \frac{P_c+E_2-E_1}{B+R}$.By analyzing the stable points of the system, five equilibrium points are obtained:$A_1(0,0)$,$A_2(0,1)$,$A_3(1,0)$,$A_4(0,0)$,$O(x^*,y^*)$.The stability of the equilibrium point can be determined by the Jacobian matrix of the system (Friedman, 1998). For details, see Eq. (10).

$$\begin{bmatrix} (1 - 2x)[R - P_g - y(B + R)] & x(x - 1)(B + R) \\ y(1 - y)(B + R) & (1 - 2y)[E_1 - P_c - E_2 + x(B + R)] \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \tag{10}$$

Friedman [11] believes that the equilibrium point must satisfy $Det(J) > 0$ and $Tr(J) < 0$ at the same time in order to become an evolutionary stable strategy (ESS) of the system. Due to the uncertainty of the system parameters, we need to distinguish several cases according to the determinant and trace of Jacobian matrix, and then discuss the stability of equilibrium points. The values of the local equilibrium points are shown in Table 2.

Table 2: Values at the local equilibrium point

	a_{11}	a_{12}	a_{21}	a_{22}
(0,0)	$R - P_g$	0	0	$E_1 - P_c - E_2$
(0,1)	$-P_g - B$	0	0	$-E_1 + P_c + E_2$
(1,0)	$-R + P_g$	0	0	$B + R + E_1 - P_c - E_2$
(1,1)	$P_g + B$	0	0	$-B - R - E_1 + P_c + E_2$
(x^*, y^*)	0	X	Y	0

According to the above analysis, we can further discuss the several situations of system evolution.Situation 1: $R < P_g$ and $R + E_1 - P_c < E_2 - B$. In this situation, the government's regulatory cost is higher than the government's fine for enterprises that do not take emission reduction measures, and the rational government will not choose the "regulation" strategy. $R + E_1 - P_c < E_2 - B$ implies a condition that is $E_1 - P_c < E_2$.It shows that regardless of government regulation or non-regulation, the benefits of enterprises not taking emission reduction measures are relatively high, so rational enterprises will choose "not take" strategy. System evolution stability results are shown in Table 3. Only $A_1(0,0)$ is the evolutionary stability point, and the corresponding evolutionary stability strategy is (non regulation, not take).

Table 3: Local stability of case 1

	DetJ	TrJ	Result
(0,0)	+	-	ESS
(0,1)	-	Uncertain	Saddle point
(1,0)	-	Uncertain	Saddle point
(1,1)	+	+	Unstable point

Table 4: Local stability of case 2

	DetJ	TrJ	Result
(0,0)	-	Uncertain	Saddle point
(0,1)	+	-	ESS
(1,0)	+	+	Unstable point
(1,1)	-	Uncertain	Saddle point

Situation 2: $R < P_g$ and $E_1 - P_c > E_2$. In this situation,the government's behavior is similar to that of the situation 1, and it will also choose the " non regulation " strategy. From $E_1 - P_c > E_2$,$R + E_1 - P_c > E_2 - B$ can be derived. It shows that no matter the government regulation or non regulation, the benefits obtained by enterprises taking emission reduction measures are relatively high. System evolution stability results are shown in Table 4.Only $A_2(0, 1)$ is the evolutionary stability point, and the corresponding evolutionary stability strategy is (non regulation, take).

Situation 3: $R < P_g$ and $-(B + R) < E_1 - P_c - E_2 < 0$. There is no change in the government's behavior, and it still chooses the strategy of " non regulation ".From $-(B + R) < E_1 - P_c - E_2 < 0$,we can know that the benefit of enterprises changes with the change of government behavior. When the government regulates, the enterprise takes the emission reduction measure to gain a lot. On the contrary, when the government does not regulate, the best choice for enterprises is not to take emission reduction measures. Therefore, the enterprise will finally choose the " not take" strategy.System evolution stability results are shown in Table 5. Only $A_1(0, 0)$ is the evolutionary stability point, and the corresponding evolutionary stability strategy is (non regulation, not take).

Table 5: Local stability of case 3

	DetJ	TrJ	Result
(0,0)	+	-	ESS
(0,1)	+	+	Unstable point
(1,0)	-	Uncertain	Saddle point
(1,1)	-	Uncertain	Saddle point

Table 6: Local stability of case 4

	DetJ	TrJ	Result
(0,0)	-	Uncertain	Saddle point
(0,1)	-	Uncertain	Saddle point
(1,0)	+	-	ESS
(1,1)	+	+	Unstable point

Situation 4: $R > P_g$ and $R + E_1 - P_c < E_2 - B$.In this situation, because the government's fine for enterprises that do not take emission reduction measures is higher than the government's regulation cost, the government will regulate enterprises when they do not take emission reduction measures. Similar to the situation 1, the inevitable choice of the enterprise is " not take" strategy. System evolution stability results are shown in Table 6. Only $A_3(1, 0)$ is the evolutionary stability point, and the corresponding evolutionary stability strategy is (regulation, not take).

Situation 5: $R > P_g$ and $E_1 - P_c > E_2$.In this situation,enterprise behavior is similar to that of the situation 1, and the "take" strategy is also the best choice. The government will choose the strategy of "non regulation " eventually, because the benefit of non regulation is greater under the premise of enterprises taking emission reduction measures. System evolution stability results are shown in Table 7. Only $A_2(0, 1)$ is the evolutionary stability point, and the corresponding evolutionary stability strategy is (non regulation, take).

Table 7: Local stability of case 5

	DetJ	TrJ	Result
(0,0)	+	+	Unstable point
(0,1)	+	-	ESS
(1,0)	-	Uncertain	Saddle point
(1,1)	-	Uncertain	Saddle point

Table 8: Local stability of case 6

	DetJ	TrJ	Result
(0,0)	-	Uncertain	Saddle point
(0,1)	-	Uncertain	Saddle point
(1,0)	-	Uncertain	Saddle point
(1,1)	-	Uncertain	Saddle point
(x^*, y^*)	+	0	Central point

Situation 6: $R > P_g$ and $-(B + R) < E_1 - P_c - E_2 < 0$.In this situation, The government will only regulate when enterprises do not take measures to reduce emissionsand only when the government regulates can enterprises take measures to reduce emissions to gain more benefits. Obviously, the government and

the enterprise will decide their own choices based on each other's behavior, and both sides have periodic behavior. System evolution stability results are shown in Table 8. There is no evolutionary stable point in the system, only one central point $O(x^*, y^*)$. The behavior of government and enterprises fluctuates around the central point.

3 Simulation design

In order to describe the interaction between the government and the enterprise in the evolutionary game more intuitively, some situations are selected below to use MATLAB software to simulate and test the evolutionary game process. This section explores the influence mechanism of system parameters and initial values on evolution stable state. The initial value is the probability that the game subject initially adopted a behavioral strategy.

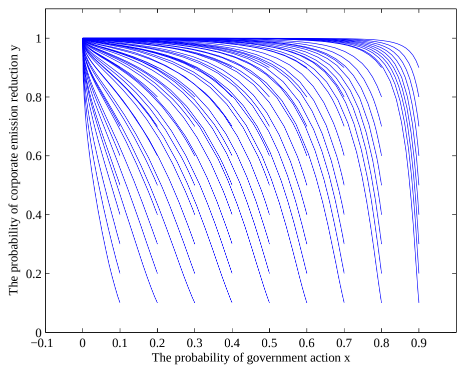

Figure 1: Dynamic evolution path for both strategies in scenario No.2

Set the parameters and adjust them according to the conditions of situation 2. Let $P_c = 30, P_g = 20, E_1 = 120, E_2 = 80, B = 40, R = 15$. These parameters are introduced into equation (9) to calculate the evolution path of the behavior of both government and enterprise. The following figure also calculates the corresponding evolution path based on equation (9). As shown in Figure 1, the vertical axis represents the probability of enterprises taking emission reduction measures y, and the horizontal axis represents the probability of government regulation x. We can find that no matter what initial value the two parties are at, they will eventually converge to (0,1), that is, (non regulation, take) strategy. The initial value here refers to the willingness of the government to initially regulate and the willingness of enterprises to initially take emission reduction measures, the same below.

Figure 2 shows the evolutionary path of government behavior in situation 2. The vertical axis represents the probability of government regulation x, and the horizontal axis represents the time t. In order to better compare and analyze the impact of different initial willingness on the evolution of the system, this paper sets the initial willingness of enterprises to take emission reduction measures and the initial willingness of government regulation as three levels, namely (0.2,0.5,0.8). On the vertical axis, the ray from 0.2, 0.5 and 0.8 respectively represents the change of the government's behavior strategy when the government's initial regulatory willingness is 0.2, 0.5 and 0.8. Red, green and blue rays represent the change of government behavior strategy when the initial value of government is fixed and the initial value of enterprise is 0.2, 0.5 and 0.8 respectively. First of all, we can find that no matter how the initial value of enterprises changes, the regulation probability of the government will fall to 0, that is, the government will ultimately choose the "non regulation" strategy. Secondly, it can be found from the figure that the red, green, and blue rays starting from a fixed endpoint (such as x= 0.8) have almost the same time to converge to 0, indicating that the initial value of the company has no significant effect on government behavior. Finally, the initial value of the government will have a greater impact on the convergence rate of its behavior probability. In the figure, when the initial value of an enterprise is determined (e.g. $y = 0.2$), the convergence time of three red rays starting from $x = 0.2$, $x = 0.5$ and $x = 0.8$ is 0.29, 0.32 and 0.36 respectively, which indicates that the greater the probability of the government initially adopting the "non regulation" strategy, the faster the probability of the government's behavior converges to 0.

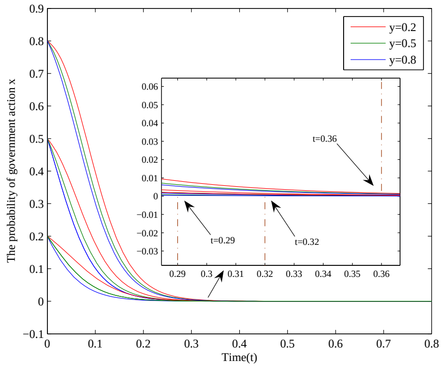

Figure 2: Dynamic evolutionary paths of government strategy in scenario No.2

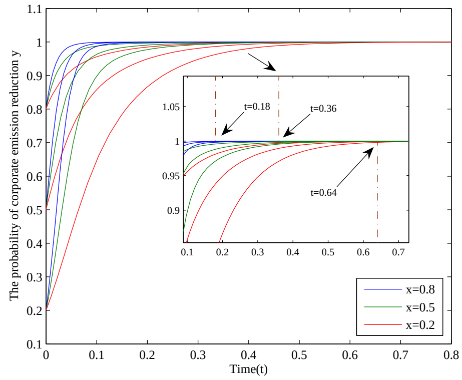

Figure 3: Dynamic evolutionary paths of enterprise strategy in scenario No.2

Figure 3 shows the evolutionary path of enterprise behavior in situation 2. The vertical axis represents the probability of enterprises taking emission reduction measures y, and the horizontal axis represents the time t. Red, green and blue rays represent the change of enterprise behavior strategy when the initial value of enterprise is fixed and the initial value of government is 0.2, 0.5 and 0.8 respectively. First of all, it can be found that no matter how the government 's initial value changes, the probability of enterprises taking carbon emission reduction measures will converge to 1, that is, enterprises will ultimately choose the "take" strategy. Secondly, the initial value of the government will affect the convergence rate of the probability of enterprise behavior.In the figure, the convergence time of three blue rays representing $x = 0.8$ is 0.18, the convergence time of three green rays representing $x = 0.5$ is 0.36, and the convergence time of three red rays representing $x = 0.2$ is 0.64.It shows that the larger the initial value of government, the faster the convergence rate of enterprise behavior probability. This phenomenon is mainly due to the government's relatively large subsidies to enterprises, and enterprises will be more sensitive to the government's regulation. Third, it can be seen from the figure that the larger the initial value of the enterprise, the faster its own convergence speed.

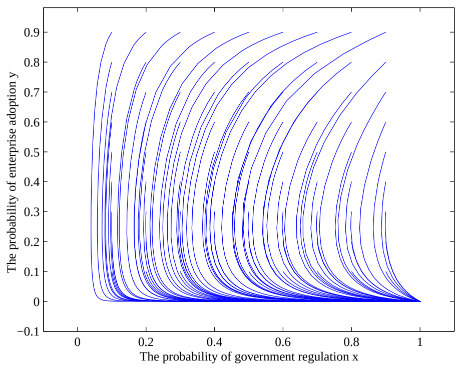

Figure 4: Dynamic evolution path for both strategies in scenario No.4

Set the parameters and adjust them according to the conditions of situation 4. Let $P_c = 30$, $P_g = 20$, $E_1 = 60$, $E_2 = 80$, $B = 20$, $R = 25$. These parameters are introduced into equation (9) to calculate the evolution path of the behavior of both government and enterprise. The results are shown in Figure 4. We can find that no matter what initial value the two parties are at, they will eventually converge to (1,0), that is, (regulation,not take) strategy.

Figure 5 shows the evolutionary path of government behavior in situation 4. On the vertical axis, the ray from 0.2, 0.5 and 0.8 respectively represents the change of the government's behavior strategy when the government's initial regulatory willingness is 0.2, 0.5 and 0.8. Red, green and blue rays represent the change of government behavior strategy when the initial value of government is fixed and the initial value of enterprise is 0.2, 0.5 and 0.8 respectively. First of all, we can find that no matter how the initial value of enterprises changes, the regulation probability of the government will converge to 1, that is, the government will ultimately choose the "regulation" strategy. Secondly, the initial value of enterprises will have an impact on government behavior, which is manifested in two aspects. First,when the initial value of enterprises is high (y= 0.8), the government will tend to be opportunistic and the probability of regulation will decrease for a short time. It is shown in the figure that the three blue rays first fall and then rise.Second, the smaller the initial value of enterprises, the faster the probability of government regulation converges to 1.In the graph, the convergence time of the red rays representing (0.8, 0.2) is 0.65, and the convergence time of the blue rays representing (0.2, 0.8) is 0.98.It shows that the smaller the initial value of enterprises, the larger the initial value of government, and the faster the convergence rate of government regulation probability.

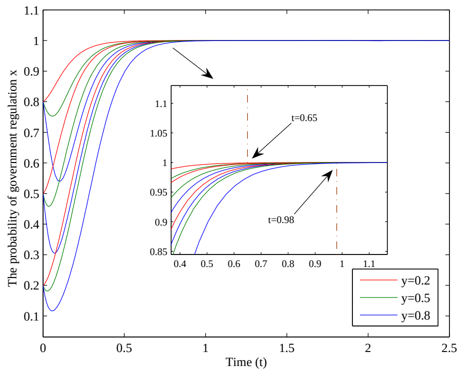

Figure 5: Dynamic evolutionary paths of government strategy in scenario No.4

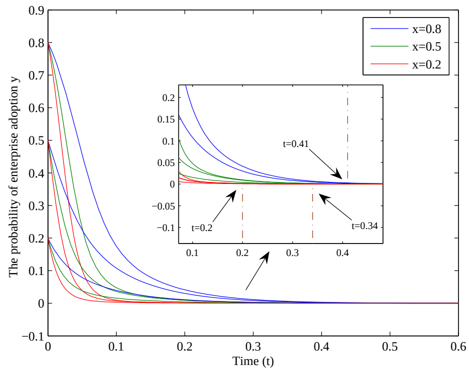

Figure 6: Dynamic evolutionary paths of enterprise strategy in scenario No.4

Figure 6 shows the evolutionary path of enterprise behavior in situation 4. Red, green and blue rays represent the change of enterprise behavior strategy when the initial value of enterprise is fixed and the initial value of government is 0.2, 0.5 and 0.8 respectively. First of all, it can be found that no matter how the government 's initial value changes, the probability of enterprises taking carbon emission reduction measures will converge to 0, that is, enterprises will ultimately choose the "not take" strategy. Secondly, the change of government initial value will have an impact on the probability of enterprise behavior.In the graph, the convergence time of blue, green and yellow ray starting from y = 0.8 is 0.41, 0.34 and 0.2, respectively.It shows that the lower the initial regulation probability of the government is, the faster the enterprise behavior probability converges to 0.Third, it can be seen from the figure that the smaller the initial value of an enterprise is, the faster its convergence speed is.

4 Conclusions

Considering the limited rational behavior of both government and enterprise, this paper constructs an evolutionary game model of carbon emission reduction between government and enterprise. Based on concrete analysis of behavioral strategies of government and enterprise in different situations, the game process is simulated and tested. The results show that there are three evolutionary stability strategies in six situations, and there is also a situation where there is no evolutionary stability point. It can be found that the government and enterprise cannot reach the optimal state (regulation, take).

The increase of emission reduction subsidies can enhance the possibility of enterprises to take emission reduction measures,while the increase of fines can enhance the enthusiasm of government regulation. This requires the establishment and improvement of a carbon emission reduction evaluation and incentive mechanism. In fact, the enthusiasm of both the government and the enterprises depends on fines and subsidies to a great extent. On the one hand, the government should make a comprehensive evaluation on the carbon emission reduction of enterprises, and increase the punishment for enterprises that do not meet the emission reduction standards. On the other hand, the government should not hesitate to provide subsidies or rewards to enterprises that actively take measures to reduce carbon emissions, so as to form an effective incentive mechanism.

The initial value of government and enterprise also has a certain influence on the evolution results, which is mainly reflected in the convergence rate. An increase in the government's initial value will promote enterprises to take emission reduction measures. Similarly, the increase of the initial value of enterprises can also strengthen the government's regulation strategy. It should be noted that in some situations, the government will have a temporary slack behavior due to the emission reduction measures of enterprises. The guiding role of policies should be strengthened. The formulation of basic targets and long-term plans for carbon emission reduction can effectively increase the possibility of government and enterprises adopting active strategies in the first place.

This paper describes the game process and behavior trajectory of government and enterprise carbon emission reduction, which lays a good foundation for further research. The model in this paper is relatively simple, and many constraints have not been taken into account, so it has not reached the optimal state of carbon emission reduction. We believe that these problems will be improved after the factors such as public willingness and carbon trading system are added. This is our future research direction.

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References

[1] J. M. Wang. Experimental research on the influence of consumers'carbon emission reduction polices. *BeijingScience Press,*2011.

[2] Y. H. Tian et al. A system dynamics model based on evolutionary game theory for green supply chain management diffusion among Chinese manufacturers. *Journal of Cleaner Production.* 80(2014):96-105.

[3] G.Li et al. Game theoretical analysis of firms' operational low-carbon strategy under various cap-and-trade mechanisms. *Journal of Cleaner Production.* 197(2018):124-133.

[4] D. Zhou et al. Would an increasing block carbon tax be better? A comparative study within the Stackelberg Game framework. *Journal of Environmental Management.* 235(2019):328-341.

[5] J. Ren et al. Game Anaysis between Government and Enterprise and the Strategy of Government Subsidies under Low-Carbon Economy. *Operations Research and Management Science.* 25(2016):258-265.

[6] Z. G.Wang et al. The Research on Government Low-carbon Regulation Guiding Enterprise Low-carbon Technology Innovation in Dynamic Game. *Chinese Journal of Management Science.* 24(2016): 139-147.

[7] S. Y. Xie. Evolutionary Game Theory Under Bounded Rationality. *Journal of Shanghai University of Finance and Economics*. 05(2011):3-9.

[8] J. Conlisk. Why bounded rationality?. *Journal of Economic Literature*. 34(1996): 669-700.

[9] H. A. Simon. Invariants of human behavior. *Annual Review of Psychology*. 41(1990):1-20.

[10] H. P. Young. Individual learning and social rationality. *European Economic Review*. 42(1998): 651-663.

[11] D. Friedman. On economic applications of evolutionary game theory. *Journal of Evolutionary Economics*. 8(1998): 15-43.