Evolutionary Game of Environmental Investment under National Environmental Regulation in China

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2 Regulation in China

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6 **Abstract:** With the rapid development of social economy, the deterioration of environment has become
7 more and more serious, it is urgent to find a balance between economic development and environmental
8 protection. Therefore, enterprises are appealed to invest in environmental protection and local
9 municipalities are appealed to supervise the environmental behaviors of enterprises, while central
10 government plays a role of regulation. In order to study the preconditions for a better environmental
11 strategy combination of local municipalities and enterprises, an evolutionary game theory was first
12 constructed in this paper, then the evolutionary stable strategy (ESS) of local municipalities and
13 enterprises under different scenarios was examined, and finally a simulation was used to test the results
14 of the analysis. The results indicate that central government's regulation has influence on the strategies
15 chosen by local municipalities and enterprises, the larger the degree of central government's incentives
16 are, the more possible local municipalities and enterprises would choose environment-friendly strategies;
17 and the intensity of central government's regulation, the cost and benefits of local municipalities'
18 supervision, and the cost and benefits of enterprises' environmental investment are the key influence
19 factors.

20 **Keywords:** Environmental regulation; Environmental investment; Evolutionary game theory; Local
21 municipalities; Central government; Simulation.

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1. Introduction

The past few decades have witnessed the rapid development of social economy, while the deterioration of environment has become matters of great concern for the international community especially in developing countries (Lo et al., 2006). Economic development and industrial advancement have not only brought the progress of world civilization, but also brought the damage of ecological environment (Tiba and Omri, 2017). Therefore, more and more countries are actively participating in the construction of environmental protection by all kinds of regulation, such as environmental taxation and other environmental incentive mechanism (Borsatto and Amui, 2019).

Like other countries, China is also facing increasingly severe environmental problems. The enormous energy consumption and astonishing pollution accompanied by economic development have brought considerable environmental issues to China and limited further economic growth of China to a certain degree (Wang, 2016a). After China participated in the First United Nations Conference on the Human Environment in 1972, China's leaders realized the significance of environmental protection; and the government's Leading Group for Environmental Protection was established in 1973, which turned into the National Environmental Protection Agency in 1988, and became the State Environmental Protection Administration in 1998 (Liu and Diamond, 2005). With the deepening of researches on environmental issues, China's environmental policies changed its focus from pollution control to ecological environment protection, and shifted from end-of-pipe treatment to source control (Zhang and Wen, 2008). Since entering the twentieth century, China has been gradually increasing the scale of environmental investment: In 2000, the total environmental investment in China was 101.49 billion CNY, and the proportion of total environmental investment to GDP was 1.02%; In 2017, the total environmental investment in China was 953.895 billion CNY, with an increase of 8.40 times over 2000, and the proportion of total environmental investment to GDP was 1.16%, only with an increase of 13.73% compared to 2000. Some scholars suggested that only when the proportion of total environmental investment to GDP reached 1%~2%, could a country control the deterioration of environmental pollution in general; and when the proportion of total environmental investment to GDP reached 3%~5%, environmental quality could take a turn for the better (Shao, 2010). Therefore, China is supposed to increase environmental investment by improving the system of environmental regulation.

Since the enactment of the *Environmental Protection Law* in 1979, China has gradually established a system of environmental regulation (Mol and Carter, 2006). China declared environmental protection as a basic national principle in 1983, set down sustainable development a basic national policy in 1992, and formulated the first five-year environmental protection plan in 1996 (Liu and Diamond, 2005; Zhang and Wen, 2008). According to the 11th five-year plan for China's economic and social development in

2005, circular economy was identified as a basic national policy of China (Feng and Yan, 2007). The *Renewable Energy Law* came into being in 2005 and was amended in 2009 (Liu, 2019). China has put in place many support policies to promote wind power development since 2003 (Zhao et al., 2016). In 2015, Environment Ministry, National Development and Reform Commission (NDRC) and National Energy Administration (NEA) jointly issued implementation plan for ultra-low emissions technical transformation of China's thermal power plants (Niu et al., 2016). NEA issued an instruction enforcing that generation enterprises have to ensure that over 9% of its total power generation come from renewable power in 2016 (Zeng et al., 2017). From January the first, 2018, the *Environmental Protection Tax Law of the People's Republic of China* came into effect, and environmental taxation was officially levied (Presley and Lin, 2018).

There are three parties in the system of China's environmental regulation: central government, local municipalities and the public (Fang et al., 2018a). Central government is generally considered as complete rationality, since central government is unwilling to obtain economic development at the cost of environmental degradation in principle. The standards of environmental regulation in China are usually formulated by central government, while the specific policies of environmental regulation in China are usually implemented by local municipalities, hence whether the environmental issues can be effectively solved depends on the implementation of local municipalities to a great extent (Zhang and Zhu, 2010). However, due to the positive externality of environmental regulation, there exists the phenomenon of free-riding among different local municipalities: some local municipalities use low intensity environmental regulation to attract capital inflows, thus promoting local economic growth (Cumberland, 1981). For the public, it includes enterprises, social organizations and individuals, and it mainly refers to enterprises in this paper. Therefore, it is important for the central government to formulate sound environmental policies, and it is also important whether local municipalities would supervise or whether enterprises would follow the policies. Due to the asymmetry of information and the influence of both external and internal environment, it is difficult for either local municipalities or enterprises to play in a completely rational way in real economy activities, their strategies are not optimal at first (Mahmoudi and Rasti-Barzoki, 2018). Local municipalities and enterprises will learn from observing or imitating successful precedents and experimenting with new strategies, and evolutionary game theory can better reflect this process.

As a subfield of game theory, evolutionary game theory was originated from genetic ecologists such as Fisher (1930) who studied the conflicts and cooperative behaviors among animals and plants. Until the concept of evolutionary stable strategy (ESS) was first proposed by Smith and Price (1973), the evolutionary game theory was born formally. ESS means that if the majority of a population choose this

strategy, few mutant individuals can never invade this population successfully; it is similar to the domain of attraction in the Nash equilibrium, unless there is a strong shock from the outside, the population will not deviate from ESS (Hines, 1987). Taylor and Jonker (1978) first proposed the concept of replicator dynamic in evolutionary game theory which represented the dynamic convergence process towards ESS, it can determine the evolution of the population over time. Different from traditional game theory, players in evolutionary game theory are considered to be bounded rational (Foxon, 2006), which means that the equilibrium is the result of constant adjustments rather than once single selection; that is, players in bounded rational game would seek better strategies through trial and error (Friedman, 1991). As players gain experience while playing the game, better strategies would be used more often than worse ones, the part of population who choose worse strategies have to change into better strategies or exit the game and disappear in the evolution process (Hofbauer and Sigmund, 1988). Nowadays, evolutionary game theory is applied to more and more fields. Some scholars used evolutionary game theory to explore medical problems, such as tumor (Malekian et al., 2016; Khadem et al., 2017) and medical applications (Chen et al., 2018a); Some scholars studied information technology problems with the utilization of evolutionary game theory, such as wireless sensor networks (Arora et al., 2016) and data warehouses (Sohrabi and Azgomi, 2019); Fields like migration (Leenheer et al., 2017) and intellectual property (Yang et al., 2018) have also been involved. And both economic and environmental issues have been widely researched by the theory of evolutionary game, such as carbon taxes (Chen and Hu, 2018), green building scheme design (Wang, 2018b), green supply chain (Babu and Mohan, 2018; Sun et al., 2019), electric vehicles (Fang et al., 2019b) and municipal solid waste source separation (Chen et al., 2018b).

Formulating effective and durable solutions to China's environmental regulation system will remain a challenge. Since environmental policies have influence on the economic system, and the influence of economic system on environmental system would affect environmental policies in turn, the environmental regulation system in China would be constantly improving, we believe that evolutionary game theory be a feasible method to study this issue.

2. Methodology

2.1. General game model

In the game of this paper, there exists a population of enterprises and a population of local municipalities who are the players of the game. All the players in the game are bounded rational, each player can calculate the consequences of its strategic choices and can make choice which best favor its interests. There are two strategies for each player: enterprises can choose to invest in environmental protection (I) which is narrow environmental investment or not invest (NI), local municipalities can choose to supervise enterprises' investment (S) which is included in broad environmental investment or

not supervise (NS). The proposed game theory model in this paper was based on the following assumptions:

(1) There are costs if enterprises choose I and local municipalities choose S, where C_E is for enterprises' costs and C_L is for local municipalities' costs.

(2) There are awards for local municipalities from central government if they choose S, such as promotion or increment of wages; and when local municipalities choose S while enterprises choose I, the awards are defined as A_1 , when local municipalities choose S while enterprises choose NI, the awards are defined as A_2 . Similarly, there are punishments for local municipalities from central government if they choose NS, such as demotion or decrement of wages; and when local municipalities choose NS while enterprises choose I, the punishments are defined as P_1 , when local municipalities choose NS while enterprises choose NI, the punishments are defined as P_2 . Both awards and punishments are the illustration of environmental index in official performance evaluation, and the quantity of awards and punishments can declare the weight of environmental index.

(3) There are subsidies for enterprises from central government if they choose I; and when enterprises choose I while local municipalities chose S, the subsidies are defined as S_1 , when enterprises choose I while local municipalities chose NS, the subsidies are defined as S_2 . There are fines (F) for enterprises from local municipalities if enterprises choose NI while local municipalities choose S, such as carbon taxes.

(4) For that (S, I) is the case that the central government most willing to obtain and (NS, NI) is the last case that the central government wants to obtain, the central government would set parameters as follows: $A_1 > A_2$, $S_1 > S_2$, $P_1 < P_2$.

(5) When enterprises choose NI, enterprises can get their original revenue (R); When enterprises choose I, enterprises can get extra revenue (ΔR) because consumers are more willing to buy environment-friendly products with the propaganda of environmental awareness.

(6) All the parameters mentioned in the above five assumptions are larger than or equal to 0.

Base on the above assumptions, the payoff matrix between local municipalities and enterprises is shown as Table 1.

Table 1 Game payoff matrix

		Enterprises	
		I	NI
Local Municipalities	S	$(-C_L + A_1, R + \Delta R - C_E + S_1)$	$(-C_L + A_2 + F, R - F)$
	NS	$(-P_1, R + \Delta R - C_E + S_2)$	$(-P_2, R)$

Let x ($0 \leq x \leq 1$) be the proportion of local municipalities who choose S, then $(1 - x)$ denote the

proportion of local municipalities who choose NS. And let y ($0 \leq y \leq 1$) be the proportion of enterprises who choose I, then $(1 - y)$ denote the proportion of enterprises who choose NI.

The expected payoffs of local municipalities are as follows:

$$\begin{aligned}\Pi_S &= y \times (-C_L + A_1) + (1 - y) \times (-C_L + A_2 + F) \\ &= -C_L + y \times A_1 + (1 - y) \times (A_2 + F) \\ \Pi_{NS} &= y \times (-P_1) + (1 - y) \times (-P_2) \\ \Pi_L &= x \times \Pi_S + (1 - x) \times \Pi_{NS}\end{aligned}\tag{1}$$

Where, Π_S represents the payoff of local municipalities who choose S, Π_{NS} represents the payoff of local municipalities who choose NS, and Π_L represents the average payoff against all possible strategies of local municipalities.

The expected payoffs of enterprises are as follows:

$$\begin{aligned}\Pi_I &= x \times (R + \Delta R - C_E + S_1) + (1 - x) \times (R + \Delta R - C_E + S_2) \\ &= R + \Delta R - C_E + x \times S_1 + (1 - x) \times S_2 \\ \Pi_{NI} &= x \times (R - F) + (1 - x) \times R \\ &= R - x \times F \\ \Pi_E &= y \times \Pi_I + (1 - y) \times \Pi_{NI}\end{aligned}\tag{2}$$

Where, Π_I represents the payoff of enterprises who choose I, Π_{NI} represents the payoff of enterprises who choose NI, and Π_E represents the average payoff against all possible strategies of enterprises.

2.2. Evolutionary game model

The speed of learning and improvement of each player is different. Repeated games in a large group of players with slower learning speeds can adopt replication dynamics. The dynamic change for the proportion of a strategy is the core of the bounded rational game analysis, and the key is the speed of dynamic change. The speed of dynamic change for the proportion of one population using a certain strategy can be reflected by the differential equation of the replication dynamics.

The replicator dynamic equation of local municipalities who choose S is as follows:

$$\begin{aligned}F_L(x) &= \frac{dx}{dt} = x \times (\Pi_S - \Pi_L) = x \times (1 - x) \times (\Pi_S - \Pi_{NS}) \\ &= x \times (1 - x) \times [-C_L + y \times (A_1 + P_1) + (1 - y) \times (A_2 + F + P_2)]\end{aligned}\tag{3}$$

When let $F_L(x) = 0$, we can obtain three stable points as follows:

$$x^* = 0$$

$$x^* = 1$$

$$y^* = \frac{C_L - (A_2 + F + P_2)}{(A_1 + P_1) - (A_2 + F + P_2)} = \frac{(-C_L + A_2 + F) - (-P_2)}{[(-C_L + A_2 + F) - (-P_2)] - [(-C_L + A_1) - (-P_1)]}$$

$$= \frac{\Pi_{S/NI} - \Pi_{NS/NI}}{(\Pi_{S/NI} - \Pi_{NS/NI}) - (\Pi_{S/I} - \Pi_{NS/I})} \quad (4)$$

Where, $\Pi_{S/NI}$ represents the payoff of local municipalities who choose S while enterprises choose NI, $\Pi_{NS/NI}$ represents the payoff of local municipalities who choose NS while enterprises choose NI, $\Pi_{S/I}$ represents the payoff of local municipalities who choose S while enterprises choose I, $\Pi_{NS/I}$ represents the payoff of local municipalities who choose NS while enterprises choose I.

Similarly, the replicator dynamic equation of enterprises who choose I is as follows:

$$F_E(y) = \frac{dy}{dt} = y \times (\Pi_I - \Pi_E) = y \times (1 - y) \times (\Pi_I - \Pi_{NI})$$

$$= y \times (1 - y) \times [\Delta R - C_E + x \times (S_1 + F) + (1 - x) \times S_2] \quad (5)$$

When let $F_E(y) = 0$, we can obtain three stable points as follows:

$$y^* = 0$$

$$y^* = 1$$

$$x^* = \frac{\Delta R - C_E + S_2}{S_2 - S_1 - F} = \frac{(R + \Delta R - C_E + S_2) - R}{[(R + \Delta R - C_E + S_2) - R] - [(R + \Delta R - C_E + S_1) - (R - F)]}$$

$$= \frac{\Pi_{I/NS} - \Pi_{NI/NS}}{(\Pi_{I/NS} - \Pi_{NI/NS}) - (\Pi_{I/S} - \Pi_{NI/S})} \quad (6)$$

Where, $\Pi_{I/NS}$ represents the payoff of enterprises who choose I while local municipalities choose NS, $\Pi_{NI/NS}$ represents the payoff of enterprises who choose NI while local municipalities choose NS, $\Pi_{I/S}$ represents the payoff of enterprises who choose I while local municipalities choose S, $\Pi_{NI/S}$ represents the payoff of enterprises who choose NI while local municipalities choose S.

According to Friedman (1991), the stability of equilibrium points could be analyzed using the Jacobian matrix, and the ESS could be obtained when the stable points satisfied both $\det(J) > 0$ and $\text{tr}(J) < 0$.

$$J = \begin{bmatrix} \frac{dF_L(x)}{dx} & \frac{dF_L(x)}{dy} \\ \frac{dF_E(y)}{dx} & \frac{dF_E(y)}{dy} \end{bmatrix} = \begin{bmatrix} d_{11} & d_{12} \\ d_{21} & d_{22} \end{bmatrix} \quad (7)$$

$$\text{Where } d_{11} = (1 - 2x) \times [-C_L + y \times (A_1 + P_1) + (1 - y) \times (A_2 + F + P_2)]$$

$$d_{12} = x \times (1 - x) \times [(A_1 + P_1) - (A_2 + F + P_2)]$$

$$d_{21} = y \times (1 - y) \times [(S_1 + F) - S_2]$$

$$d_{22} = (1 - 2y) \times [\Delta R - C_E + x \times (S_1 + F) + (1 - x) \times$$

$$S_2] \quad (8)$$

Then the value of each term above at five possible stable points can be obtained in Table 2.

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Table 2 Term value of Jacobian matrix at each stable point

Stable point	d_{11}	d_{12}	d_{21}	d_{22}
(0,0)	$-C_L + (A_2 + F + P_2)$	0	0	$\Delta R - C_E + S_2$
(0,1)	$-C_L + (A_1 + P_1)$	0	0	$C_E - \Delta R - S_2$
(1,0)	$C_L - (A_2 + F + P_2)$	0	0	$\Delta R - C_E + (F + S_1)$
(1,1)	$C_L - (A_1 + P_1)$	0	0	$C_E - \Delta R - (F + S_1)$
(x^*, y^*)	0	$x^* \times (1 - x^*)$ $\times [(A_1 + P_1)$ $-(A_2 + F + P_2)]$	$y^* \times (1 - y^*)$ $\times [(S_1 + F)$ $- S_2]$	0

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3. Results and analyses

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According to the rule of Jacobian matrix, when d_{11} and d_{22} are both smaller than 0 as well as d_{12} and d_{21} have opposite sign or both equal to 0, the stable point must be ESS; otherwise, it is indeterminate.

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First, for that d_{11} and d_{22} are both 0 at (x^*, y^*) , $tr(J) < 0$ can never be satisfied, thus (x^*, y^*) can never be an ESS. Moreover, d_{12} and d_{21} always equal to 0 at other possible stable points, so there are only four different scenarios to analyze in line with the sign of d_{11} and d_{22} . The analyses are demonstrated in Tables 3-6 as follows.

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Table 3 Analysis of scenario 1: $(A_2 + F + P_2) < C_L$ and $(\Delta R + S_2) < C_E$

Stable point	$det(J)$	$tr(J)$	Result
(0,0)	+	−	ESS
(0,1)	Uncertain	Uncertain	Unstable
(1,0)	Uncertain	Uncertain	Unstable
(1,1)	Uncertain	Uncertain	Unstable

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It is obvious from **Table 3** that when $(A_2 + F + P_2) < C_L$ and $(\Delta R + S_2) < C_E$, the ESS is (0,0), that is, local municipalities choose NS and enterprises choose NI. It is because the difference between awards and punishments is smaller than the cost of supervisory and the totaling of subsidies and extra revenue is smaller than the cost of environmental investment.

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Table 4 Analysis of scenario 2: $(A_1 + P_1) < C_L$ and $(\Delta R + S_2) > C_E$

Stable point	$det(J)$	$tr(J)$	Result
(0,0)	Uncertain	Uncertain	Unstable
(0,1)	+	–	ESS
(1,0)	Uncertain	Uncertain	Unstable
(1,1)	–	Uncertain	Unstable

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It can be concluded from **Table 4** that when $(A_1 + P_1) < C_L$ and $(\Delta R + S_2) > C_E$, the ESS is (0,1), that is, local municipalities choose NS while enterprises choose I. It is because the difference between awards and punishments is smaller than the cost of supervisory, but the totaling of subsidies and extra revenue is larger than the cost of environmental investment.

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Table 5 Analysis of scenario 3: $(A_2 + F + P_2) > C_L$ and $(\Delta R + S_1 + F) < C_E$

Stable point	$det(J)$	$tr(J)$	Result
(0,0)	–	Uncertain	Unstable
(0,1)	Uncertain	Uncertain	Unstable
(1,0)	+	–	ESS
(1,1)	Uncertain	Uncertain	Unstable

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It is clear from **Table 5** that when $(A_2 + F + P_2) > C_L$ and $(\Delta R + S_1 + F) < C_E$, the ESS is (1,0), that is, local municipalities choose S while enterprises choose NI. It is because the difference between awards and punishments is larger than the cost of supervisory, but the totaling of subsidies and extra revenue is smaller than the cost of environmental investment.

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Table 6 Analysis of scenario 4: $(A_1 + P_1) > C_L$ and $(\Delta R + S_1 + F) > C_E$

Stable point	$det(J)$	$tr(J)$	Result
(0,0)	Uncertain	Uncertain	Unstable
(0,1)	Uncertain	Uncertain	Unstable
(1,0)	Uncertain	Uncertain	Unstable
(1,1)	+	–	ESS

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It can be seen from **Table 6** that when $(A_1 + P_1) > C_L$ and $(\Delta R + S_1 + F) > C_E$, the ESS is (1,1), that is, local municipalities choose S and enterprises choose I. It is because the difference between awards and punishments is larger than the cost of supervisory and the totaling of subsidies and extra revenue is larger than the cost of environmental investment.

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From Tables 3-6 above-mentioned, the following conclusions can be drawn: As long as $(A_1 + P_1) > C_L$ and $(\Delta R + S_1 + F) > C_E$, the ESS is or is possible to be (1,1), and that is the case the central government most willing to obtain; As long as $(A_1 + P_1) < C_L$ and $(\Delta R + S_2) > C_E$, the ESS is (0,1),

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and that is the case the central government second willing to obtain; As long as $(A_2 + F + P_2) > C_L$ and $(\Delta R + S_1 + F) < C_E$, the ESS is (1,0); Once $(A_2 + F + P_2) < C_L$ and $(\Delta R + S_2) < C_E$, the ESS is (0,0). In other words, if the central government expect enterprises to invest in environmental protection, while it cannot guarantee that the totaling of A_1 and P_1 is larger than the cost of supervisory for local municipalities, it has to raise subsidies or arouse more willingness of consumers for environment-friendly products to maintain the totaling of subsidies and extra revenue larger than the cost of environmental investment.

4. Simulations and discussions

In this section, the evolution of this environmental regulation system was further clarified based on the results simulated by *Matlab*. In order to better illustrate the influence of central government's regulation on players' strategies, we had defined the regulation coefficients for both local municipalities and enterprise as follows:

$$a_1 = \frac{A_1 - (-P_1)}{C_L} ; a_2 = \frac{(A_2 + F) - (-P_2)}{C_L}$$

$$b_1 = \frac{S_1 - (-F)}{C_E - \Delta R} ; b_2 = \frac{S_2}{C_E - \Delta R} \quad (9)$$

a_1 indicates the regulation coefficient for local municipalities when enterprises choose I, the larger a_1 is, the larger the degree of central government's incentives (awards or punishments) are; if we regard $-P_1$ as the opportunity cost of local municipalities for choosing S, then $A_1 - (-P_1)$ could represent the actual yield of local municipalities for choosing S, and $a_1 \geq 1$ indicates that what local municipalities obtain for choosing S can cover what they expend for supervisory. Similarly, a_2 indicates the regulation coefficient for local municipalities when enterprises choose NI, b_1 indicates the regulation coefficient for enterprises when local municipalities choose S, b_2 indicates the regulation coefficient for enterprises when local municipalities choose NS. And according to the assumptions (4) and (6) in Section 2.1, we can obtain that $b_1 > b_2$.

After the definition of regulation coefficients, equations (3) and (6) could be simulated by function *ode45* with the usage of *Matlab*. Except for the three variables t, x, y , the value assignment of the rest parameters was randomly assigned on the premise that the conditions of each scenario were met, particular value as 0.5, multiple value and exponent value were not used specifically; and the initial value of x and y were both set to be 0.5, t was increased from 0 at the step of 0.1.

4.1 ESS (0, 0): $(A_2 + F + P_2) < C_L$ and $(\Delta R + S_2) < C_E$

In this scenario, we were supposed to satisfy the precondition of $a_2 < 1$ and $b_2 < 1$ first, then we assigned a_2 as 0.65 and b_2 as 0.75, a_1 and b_1 were assigned respectively from sets {0.3, 0.8, 1.3}

and $\{0.9, 1.4\}$. The simulation results are shown as Fig. 1: The first line of “ $a_1 < a_2 < 1, b_2 < b_1 < 1$ ” at the upper right represents that $a_1 = 0.3, a_2 = 0.65, b_1 = 0.9, b_2 = 0.75$, the representations of other lines can be obtained by permutation and combination of the above value assignments in the same way; And the left graph in Fig. 1 represents the trend for the proportion of local municipalities who choose S, the right graph in Fig. 1 represents the trend for the proportion of enterprises who choose I with t increases.

Fig. 1 Simulation results of ESS (0, 0).

It is obvious from Fig. 1 that as long as $a_2 < 1$ and $b_2 < 1$ are satisfied, no matter how a_1 and b_1 change, x and y would gradually approach 0 as time passes, that is, local municipalities would choose NS and enterprises would choose NI. For x , since the lines “ $a_1 < a_2 < 1, b_2 < b_1 < 1$ ” and “ $a_1 < a_2 < 1, b_2 < 1 < b_1$ ” are perfectly coincided, the lines “ $a_2 < a_1 < 1, b_2 < b_1 < 1$ ” and “ $a_2 < a_1 < 1, b_2 < 1 < b_1$ ” are perfectly coincided, and the lines “ $a_2 < 1 < a_1, b_2 < b_1 < 1$ ” and “ $a_2 < 1 < a_1, b_2 < 1 < b_1$ ” are almost coincided, the variation of regulation coefficients for enterprises nearly has no influence on x when the regulation coefficients for local municipalities remain unchanged; Since the lines “ $a_1 < a_2 < 1, b_2 < b_1 < 1$ ” and “ $a_2 < a_1 < 1, b_2 < b_1 < 1$ ” are more concave towards the horizontal axis than the line “ $a_2 < 1 < a_1, b_2 < b_1 < 1$ ”, the smaller a_1 and a_2 are, especially when they are smaller than 1, the quicker x would approach to 0. Similar for y , since the lines “ $a_1 < a_2 < 1, b_2 < b_1 < 1$ ”, “ $a_2 < a_1 < 1, b_2 < b_1 < 1$ ” and “ $a_2 < 1 < a_1, b_2 < b_1 < 1$ ” are perfectly coincided, the lines “ $a_1 < a_2 < 1, b_2 < 1 < b_1$ ”, “ $a_2 < a_1 < 1, b_2 < 1 < b_1$ ” and “ $a_2 < 1 < a_1, b_2 < 1 < b_1$ ” are almost coincided, the variation of regulation coefficients for local municipalities nearly has no influence on y when the regulation coefficients for enterprises remain unchanged; Since the lines “ $a_1 < a_2 < 1, b_2 < 1 < b_1$ ”

$b_1 < 1$ ” are more concave towards the horizontal axis than the line “ $a_1 < a_2 < 1, b_2 < 1 < b_1$ ”, the smaller b_1 and b_2 are, the quicker y would approach to 0.

4.2 ESS (0, 1): $(A_1 + P_1) < C_L$ and $(\Delta R + S_2) > C_E$

In this scenario, after the satisfaction of the precondition $a_1 < 1$ and $b_2 > 1$, then we assigned a_1 as 0.7 and b_2 as 1.2, a_2 was assigned randomly from set $\{0.3, 0.8, 1.3\}$, and b_1 was assigned as 1.45 since $b_1 > b_2$ was calculated. The simulation results are shown as Fig. 2.

Fig. 2 Simulation results of ESS (0, 1).

It can be clearly seen from Fig. 2 that as long as $a_1 < 1$ and $b_2 > 1$ are satisfied, no matter how a_2 and b_1 change, x would gradually approach 0 and y would gradually approach 1 as time passes, that is, local municipalities would choose NS and enterprises would choose I. On account of $b_2 > 1$ and $b_1 > b_2$, we can only have $1 < b_2 < b_1$ in this scenario. For x , since the lines “ $a_2 < a_1 < 1, 1 < b_2 < b_1$ ” and “ $a_1 < a_2 < 1, 1 < b_2 < b_1$ ” are perfectly coincided, while the line “ $a_1 < 1 < a_2, 1 < b_2 < b_1$ ” is not, the variation of a_1 and a_2 nearly has no influence on x when they are both smaller than 1 and the regulation coefficients for local municipalities remain unchanged; Since the lines “ $a_2 < a_1 < 1, 1 < b_2 < b_1$ ” and “ $a_1 < a_2 < 1, 1 < b_2 < b_1$ ” are more concave towards the horizontal axis than the line “ $a_1 < 1 < a_2, 1 < b_2 < b_1$ ”, the smaller a_1 and a_2 are, especially when they are smaller than 1, the quicker x would approach to 0. Similar for y , since the lines “ $a_2 < a_1 < 1, 1 < b_2 < b_1$ ”, “ $a_1 < a_2 < 1, 1 < b_2 < b_1$ ” and “ $a_1 < 1 < a_2, 1 < b_2 < b_1$ ” are perfectly coincided, the variation of regulation coefficients for local municipalities nearly has no influence on y when the regulation coefficients for enterprises remain unchanged.

4.3 ESS (1, 0): $(A_2 + F + P_2) > C_L$ and $(\Delta R + S_1 + F) < C_E$

In this scenario, after the satisfaction of the precondition $a_2 > 1$ and $b_1 < 1$, then we assigned a_2 as 1.3 and b_1 as 0.7, a_1 was assigned randomly from set $\{0.3, 1.1, 1.6\}$, and b_2 was assigned as 0.4 since $b_1 > b_2$ was calculated. The simulation results are shown as Fig. 3.

Fig. 3 Simulation results of ESS (1, 0).

It can be clearly seen from Fig. 3 that as long as $a_2 > 1$ and $b_1 < 1$ are satisfied, no matter how a_1 and b_2 change, x would gradually approach 1 and y would gradually approach 0 as time passes, that is, local municipalities would choose S and enterprises would choose NI. On account of $b_1 < 1$ and $b_1 > b_2$, we can only have $b_2 < b_1 < 1$ in this scenario. For x , all the lines are not coincided at all, and combined with the Fig. 1 and Fig. 2, we could obtain that the variation of a_1 and a_2 does have influence on x when they are both larger than 1 and the regulation coefficients for local municipalities remain unchanged; Since the line “ $1 < a_2 < a_1, b_2 < b_1 < 1$ ” is most concave towards the line $x = 1$, sequentially are “ $a_1 < 1 < a_2, b_2 < b_1 < 1$ ” and “ $1 < a_1 < a_2, b_2 < b_1 < 1$ ”, the larger a_1 and a_2 are, especially when they are larger than 1, the quicker x would approach to 1, and a_1 has a greater influence on x than a_2 . Similar for y , since the lines “ $1 < a_2 < a_1, b_2 < b_1 < 1$ ”, “ $a_1 < 1 < a_2, b_2 < b_1 < 1$ ” and “ $1 < a_1 < a_2, b_2 < b_1 < 1$ ” are perfectly coincided, the variation of regulation coefficients for local municipalities nearly has no influence on y when the regulation coefficients for enterprises remain unchanged.

4.4 ESS (1, 1): $(A_1 + P_1) > C_L$ and $(\Delta R + S_1 + F) > C_E$

In this scenario, after the satisfaction of the precondition $a_1 > 1$ and $b_1 > 1$, then we assigned a_1 as 1.3 and b_1 as 1.6, a_2 and b_2 were assigned respectively from sets $\{0.6, 1.2, 1.7\}$ and $\{0.7, 1.1\}$.

340 The simulation results are shown as Fig. 4.

341
342 **Fig. 4 Simulation results of ESS (1, 1).**

343 It is evident from Fig. 4 that only if $a_1 > 1$ and $b_1 > 1$ are satisfied, no matter how a_2 and b_2
344 change, x and y would gradually approach 1 as time passes, that is, local municipalities would choose
345 S and enterprises would choose I. For x , since the lines “ $a_2 < 1 < a_1, 1 < b_2 < b_1$ ” and “ $a_2 < 1 <$
346 $a_1, b_2 < 1 < b_1$ ” are perfectly coincided, the lines “ $1 < a_2 < a_1, b_2 < b_1 < 1$ ” and “ $1 < a_2 < a_1, b_2 <$
347 $1 < b_1$ ” are perfectly coincided, and the lines “ $1 < a_1 < a_2, 1 < b_2 < b_1$ ” and “ $1 < a_1 < a_2, b_2 < 1 <$
348 b_1 ” are perfectly coincided, the variation of regulation coefficients for enterprises nearly has no influence
349 on x when the regulation coefficients for local municipalities remain unchanged; Since the line “ $a_2 <$
350 $1 < a_1, 1 < b_2 < b_1$ ” is most concave towards the line $x = 1$ ”, sequentially are “ $1 < a_2 < a_1, b_2 <$
351 $b_1 < 1$ and “ $1 < a_1 < a_2, 1 < b_2 < b_1$ ”, the larger a_1 and a_2 are, especially when they are larger
352 than 1, the quicker x would approach to 1. Similar for y , since all the lines are perfectly coincided, the
353 variation of regulation coefficients for local municipalities nearly has no influence on y when the
354 regulation coefficients for enterprises remain unchanged, and the variation of b_2 nearly has no influence
355 on y when b_1 remains larger than 1.

356 5. Conclusions

357 Under the conditions of information asymmetry and bounded rational, the evolutionary game theory
358 was used to study the environmental investment of enterprises, and an evolutionary game model of local
359 municipalities and enterprises under the regulation of central government was constructed in this paper.
360 By analyzing the replicator dynamic equations, evolutionary stability strategies were derived, and a
361 simulation of ESS was conducted in four scenarios by *Matlab*. The results show that the intensity of

central government's regulation, the cost and benefits of local municipalities' supervision, and the cost and benefits of enterprises' environmental investment are the key factors affecting the evolutionary game between government and enterprises. The implications for central government's environmental regulation were drawn from both local municipalities' and enterprises' perspectives in this paper.

From the perspective of local municipalities, the implications are as follows: (1) Central government could increase the awards for local municipalities if they choose to supervise, awards could include promotion, increment of wages, social benefits like propaganda to get popular support; (2) Central government could also enhance the intensity of punishments for local municipalities if they choose not to supervise, punishments could include demotion, decrement of wages, social losses like public criticism; (3) Meanwhile, local municipalities could increase fines for enterprises to offset the cost of supervisory if enterprises choose to not invest in environmental protection, fines could include carbon tax, resource tax, noise tax and so on. The three measures mentioned above could increase the motivation of local municipalities for supervisory to a certain extent.

From the perspective of enterprises, the implications are as follows: (1) Central government could increase the subsidies for enterprises if they choose to invest in environmental protection, subsidies could include fiscal allotment, soft loans, tax incentives and exemptions; (2) Similarly, local municipalities could increase fines for enterprises if they choose to not invest in environmental protection; (3) Central government could popularize environmental education among the public to arouse their willingness for purchasing environment-friendly products, thereby increase the extra revenue of enterprises if they choose environmental investment, environmental education could include environmental public service advertising; (4) Enterprises could increase investment in research and development of environmental technologies to produce environment-friendly products with same costs, which equivalent to the increase of the extra revenue for enterprises if they choose environmental investment.

One of the limitation of this paper was that central government was considered to be perfect rational which was inconsistent with the reality; the environmental regulation policies of central government ought to be evolved as time passes. Moreover, the value assignment of parameters was randomly generated, real data can be used to examine this evolutionary game model of environmental regulation in future research.

391 **Declarations**

392 **Ethics approval and consent to participate**

393 Not applicable.

394 **Consent for publication**

395 Not applicable.

396 **Availability of data and materials**

397 There is no actual data in this paper.

398 **Competing interests**

399 The authors declare that they have no competing interests.

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402 **Authors' contributions**

403 TS proposed the core idea and revised this manuscript, QF was the major contributor in writing the
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Figures

Figure 1

Simulation results of ESS (0,0).

Figure 2

Simulation results of ESS (0,1).

Figure 3

Simulation results of ESS (1,0).

Figure 4

Simulation results of ESS (1,1).