Research on Evolutionary Game of China's Environmental Governance System

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Abstract. The construction of environmental governance system is attracting more attention. Using game-based learning theory for reference, this paper builds an evolutionary model among central government, local government and enterprises in the context of fiscal decentralization system. The findings suggest that three parties reach an effective and stable solution under the scenario of low fiscal decentralization, active governance, and up-to-standard pollution control. Furthermore, suggestions such as a combination between governments, the increase of environmental protection expenditure and strengthening political constraints are recommended.

1. Introduction
The construction of ecological civilization is crucial for the sustainable development of the Chinese nation. The government has launched a series of reform measures to enhance the ability of environmental governance such as the Central Environmental Supervision system and environmental taxes system. The above policies and measures provide a realistic basis for the discussion of an effective environmental governance mechanism for the participation of multiple entities, including the central government, the local government and the enterprises.

The structure of the paper is as follows. Section 2 presents previous studies on the fiscal decentralization and environmental governance. A payment function of three parties will be obtained in section 3. In section 4, the model will be solved mathematically through the evolutionarily stable strategy (ESS). The numerical simulation and sensitivity analysis will be carried out in section 5. In the last part, the research conclusions will be put forward according to the analysis process.

2. Literature review
To build a modern environmental governance system, it needs placing within the important framework of the national fiscal and taxation system. The first generation of fiscal decentralization theory advocates that a high degree of fiscal decentralization promotes the provision of public goods, such as a better environment [1], the second generation believes that local governments driven by tax incentives and investment may unilaterally pursue economic growth while ignoring environmental issues [2,3]. Some scholars have explored the impacts of the ‘fiscal decentralization model with Chinese characteristics’ on environmental governance. There are three main existing viewpoints of empirical researches: High fiscal decentralization is not conducive to environmental quality [4], fiscal decentralization does not have a significant impact on environmental pollution [5], or there is an
3. Building of Evolutionary Game Model

3.1 Prerequisites and Hypothesis

Prerequisite 1: The central government, local governments, and enterprises involved in the environmental regulatory system are denoted as \(C, S, P\) respectively with limited rationality.

Prerequisite 2: All the three parties in the system have two optional strategies: the central government can choose between 'low fiscal decentralization degree' and 'high fiscal decentralization degree' strategies, local governments can choose 'active governance' and 'negative governance' strategies, and the enterprises can choose 'up-to-standard emission reduction' or 'excess emission'.

Prerequisite 3: The number of three types of game players is regarded as relatively stable. At time \(t\), the probability of the central government choosing 'low fiscal decentralization degree' is \(x(t)\), that of local governments choosing 'active governance' is \(y(t)\), and that of the enterprises choosing 'up-to-standard emission reduction' is \(z(t)\). All of the above satisfies the condition \(x(t), y(t), z(t) \in [0,1]\)

Based on China's environmental governance system reality, the following model hypotheses are made:

Hypothesis 1: If the central government chooses 'low fiscal decentralization' strategy, it will formulate a higher proportion of central tax revenue (\(\alpha\)) and carry out transfer payments (\(T\)). Otherwise, a lower proportion of tax revenue will be formulated (\(\beta\)), and no transfer payments are made. The central government will insist on implementing a central environmental supervision system (cost: \(C_1\))

Hypothesis 2: If the local government chooses the 'active governance' strategy, it will carry out an environmental tax rate (\(t_3\)) that is higher than basic tax rate. More environmental financial expenditures (\(C_3\)) will occur, and the emission reduction subsidies (\(\theta\)) will be given to enterprises. Otherwise, they will follow the national basic tax rate (\(t_1\)), a lower environmental protection expenditure (\(C_1\)), and provide no financial subsidies.

Hypothesis 3: If a company chooses the strategy of 'up-to-standard emission reduction', it will reduce production (\(N\)) based on the original output (\(Q\)) and pay unit emission reduction cost (\(\lambda\)). Otherwise, it will maintain the original output (\(Q\)) and will not generate emission reduction costs.

Hypothesis 4: Excess emission of enterprises will cause ecological losses equivalent to \(H\) to all levels of government. Local governments advocating 'active governance' will impose fines on illegal companies in their regions. The central government will impose a penalty (\(F_p\)) to "excess emission" enterprises in the 'active governance' district, and a political punishment (\(R\)) to the certain local government.

Let \(A = tpN, B = tPQ, D = F_2-T, G = (1-\alpha)T-(1-\beta)F_2, I = H+R, J = \theta+\Delta \mu, K = (2t_3-t_3)Q-NJ+\lambda F_2-H\Delta c, L = \lambda+P+\xi T, M = (\alpha-\beta)F_1, C \), \(S = T-(1-\beta)B, \mu = (\alpha-\beta)(1-\beta), \xi = \alpha-\beta, \Delta t = t_1-t_3, \Delta c = C_3-C_1\) where \(A, B, C, I, J, L, M, \mu, \Delta \xi, \Delta c \in (0, \infty), \alpha, \beta \in (0, \infty), a > \beta, \xi > 0, \text{and } (1-t)P_t > (1-t)P_t > 0\).

3.2 Building of Payment Functions

According to the preconditions and hypothesis, the payment function matrix of the central government, local governments and enterprises can be drawn (figure 1).
Analysis of Evolutionary Game Model

4.1 Replicated Dynamic Equations

In this section, the formation conditions and process will be revealed by the solution of a three-party replication dynamic equation.

4.1.1 The Replicated Dynamic Equations of the Central Government. Assuming that $U_c$ is the central government's expectation of income if it adopts low fiscal decentralization and $U^c$ is that if high fiscal decentralization, then:

$$
U_c = y(z\alpha + (1-y)\beta) + (1-z)[(\alpha - \beta)\beta P - (\alpha - \beta)k + (1-x)]z \left[(\alpha - \beta)\beta Q - (\alpha - \beta)i + (1-x)\beta P + (1-y)\beta P - (1-x)\beta P - (1-y)\beta P \right]
$$

$$
U^c = z\alpha + (1-y)\beta) + (1-z)[(\alpha - \beta)\beta P - (\alpha - \beta)k + (1-x)]z \left[(\alpha - \beta)\beta Q - (\alpha - \beta)i + (1-x)\beta P + (1-y)\beta P - (1-x)\beta P - (1-y)\beta P \right]
$$

The average payment by the central government when making strategic choices is:

$$
\bar{U}_c = xU_c + (1-x)U^c
$$

To sum up, the replicated dynamic equation of the central government is:

$$
\dot{X}_c = x \left[(\alpha - \beta)\beta P - (\alpha - \beta)k + (1-x)]z \left[(\alpha - \beta)\beta Q - (\alpha - \beta)i + (1-x)\beta P + (1-y)\beta P - (1-x)\beta P - (1-y)\beta P \right]
$$

4.1.2 The Replicated Dynamic Equations of local governments. Assuming $U_s$ is the expected benefits of local governments if they actively implement environmental governance and $U^s$ is that if negatively, then,

$$
U_s = x[(\alpha - \beta)\beta P - (\alpha - \beta)k + (1-x)]z \left[(\alpha - \beta)\beta Q - (\alpha - \beta)i + (1-x)\beta P + (1-y)\beta P - (1-x)\beta P - (1-y)\beta P \right]
$$

$$
U^s = x[(\alpha - \beta)\beta P - (\alpha - \beta)k + (1-x)]z \left[(\alpha - \beta)\beta Q - (\alpha - \beta)i + (1-x)\beta P + (1-y)\beta P - (1-x)\beta P - (1-y)\beta P \right]
$$
The average payment by the local governments when making strategic choices is:
\[ \bar{U}_c = yU_c + (1-y)U_z \] (7)

To sum up, the replicated dynamic equation of the central government is:
\[ \dot{y} = \frac{dy}{dt} = yU_c - \bar{U}_c = y(1-y)[z_t, (Q-N) + \Delta tQ-z\theta N - (1-\beta)zxtpQ + xzT + F_c + R + zt, N - zH - zR - \Delta c] \] (8)

4.1.3 The Replicated Dynamic Equations of the Enterprises. Assuming \( U_\theta \) is the expected benefits of the enterprises if they choose " up-to-standard emission reduction" and \( U_\gamma \) is that if "excess emission", then:
\[ U_\gamma = xy[(1-t) pQ-t_s Q-F_s] + (1-x)y[(1-t) pQ-t_s Q-F_s] + x(1-y)[(1-t) pQ-t_s Q-F_s] \] (9)
\[ U_\gamma = xy[(1-t) pQ-t_s Q-F_s] + (1-x)y[(1-t) pQ-t_s Q-F_s] + x(1-y)[(1-t) pQ-t_s Q-F_s] \] (10)

The average payment by the enterprises when making strategic choices is:
\[ \bar{U}_p = zU_p + (1-z)U_\gamma \] (11)

To sum up, the replicated dynamic equation of the enterprises when making strategic choices is:
\[ \dot{z} = \frac{dz}{dt} = (1-z)[y(t_s - t_c)N + t_s, N + y\theta N - (1-t)PN - \lambda N + yF_s + xF_s + xyF_s] \] (12)

4.2 Analysis of Evolutionary Game System Equilibrium Point
The three-dimensional dynamic system (I) can be composed of the above equations:
\[ X = \frac{dx}{dt} = x(1-x)[(a-\beta) tPQ - z(\alpha-\beta) tPN + F_s - zF_s - T] = x(1-x)C(x, y, z) \] (13)
\[ Y = \frac{dy}{dt} = y(1-y)[zt, (Q-N) + (t_s - t_c) Q - z\theta N - (1-\beta)zxtpQ + xzT + F_c + R + zt, N - zH - zR + C_s, C_s] \] (14)
\[ \dot{Z} = \frac{dz}{dt} = z(1-z)[y(t_s - t_c)N + t_s, N + y\theta N - (1-t)PN - \lambda N + yF_s + xF_s + xyF_s] = z(1-z)U(x, y, z) \] (15)

To solve the three-dimensional dynamic systems (I), if \( X = 0, Y = 0, Z = 0 \), it can be divided into three types of solutions:

i) The first type: a pure strategy of three populations, they are (0,0,0), (0,0,1), (0,1,0), (1,0,0), (1,1,0), (1,0,0), (0,1,1), (1,1,1) respectively.

ii) The second type: a pure strategy of two populations. Such solutions do not exist after verification.

iii) The third type: a pure strategy of a single population. The above equations have 4 equilibrium points:
\[ \begin{pmatrix}
(1-t) PN + \lambda N & -N & C_s - C_s - F_s - R - (t_s - t_c) Q \\
(t_s - t_c) N + (N - t_s, N) - t_s, (Q-N) - \theta N - t_s, N - H - R & F_s & (1-t) PN + \lambda N + C_s - C_s - F_s - R - (t_s - t_c) Q \\
(1-t) PN + \lambda N & -N & C_s - C_s - F_s - R - (t_s - t_c) Q \\
(t_s - t_c) N + (N - t_s, N) - t_s, (Q-N) - \theta N - t_s, N - H - R & F_s & (1-t) PN + \lambda N + C_s - C_s - F_s - R - (t_s - t_c) Q
\end{pmatrix}
\]
iv) The fourth type: When $\dot{X} = 0, \dot{Y} = 0, \dot{Z} = 0$, equations have a mixed strategy solution $(x^*, y^*, z^*)$:

$$
x^* = \frac{F_K + T(1 + NJ - Q_0) + A(\alpha - \beta)(E + Q\Delta) + B(\alpha - \beta)(Q_0 - I - NJ)}{(1 - \beta)B - T[D + (\alpha - \beta)B]}
$$

$$
y^* = \frac{-F_K + T(1 + NJ - Q_0) + A(\alpha - \beta)(E + Q\Delta) + B(\alpha - \beta)(Q_0 - I - NJ)}{(1 - \beta)B - T[D + (\alpha - \beta)B]}
$$

$$
z^* = \frac{-F_K + T(1 + NJ - Q_0) + A(\alpha - \beta)(E + Q\Delta) + B(\alpha - \beta)(Q_0 - I - NJ)}{(1 - \beta)B - T[D + (\alpha - \beta)B]}
$$

4.3 The Stability Analysis of the Equilibrium Points

According to Lyapunov stability theory, the stability of the system at the equilibrium point can be identified by whether the Jacobi Matrix is positive definite or negative definite. Therefore, we will first build the Jacobi matrix by solving the partial derivative of the replicated dynamic equations:

$$
O = \begin{pmatrix}
    (1-2x)[(\alpha - \beta)(B-x)A + D-zF_x] & 0 & x(1-x)[(\alpha - \beta)A - F_x] \\
    y(1-y)zS & (1-2y)[(z_1 + \Delta)Q - zJ + z + E - x'] & y(1-y)[1 - Q - J + zS - I] \\
    z(1-z)[yF_x + F_y] & (1-2z)[yJ + (1-\alpha)F_x + zF_y + (1-\alpha)F_y] & x^*(1-x) - (1 - 2x)\frac{(\alpha - \beta)B + D}{(\alpha - \beta)A + F_y}
\end{pmatrix}
$$

Take 13 equilibrium points to identify its evolutionary stability. The evolution stability conditions of system (I) at the remaining equilibrium points can be obtained (Table 1 and Table 2).

**Table 1. The equilibrium points and eigenvalues of system (I)**

| equilibrium points | $\lambda_1$ | $\lambda_2$ | $\lambda_3$ | evolution stability |
|--------------------|-------------|-------------|-------------|---------------------|
| $(0, 0, 0)$         | $(\alpha - \beta)B + D$ | $\Delta Q + E$ | $(1 - 2x)N$ | Not stable          |
| $(0, 0, 1)$         | $(\alpha - \beta)(B \cdot A) - T$ | $K$ | $(1 - 2x)N$ | Not stable          |
| $(0, 1, 0)$         | $(\alpha - \beta)B + D$ | $\Delta Q + E$ | $(1 - 2x)N + F_x$ | condition ① |
| $(1, 0, 0)$         | $(\alpha - \beta)(B \cdot A) - T$ | $K$ | $(1 - 2x)N + F_x$ | Not stable          |
| $(0, 1, 1)$         | $(\alpha - \beta)B + D$ | $\Delta Q + E$ | $(1 - 2x)N + F_x$ | condition ② |
| $(1, 0, 1)$         | $(\alpha - \beta)(B \cdot A) - T$ | $K$ | $(1 - 2x)N + F_x$ | condition ② |
| $(1, 1, 0)$         | $(\alpha - \beta)B + D$ | $\Delta Q + E$ | $(1 - 2x)N + F_x$ | condition ② |
| $(1, 1, 1)$         | $(\alpha - \beta)(B \cdot A) - T$ | $K$ | $(1 - 2x)N + F_x$ | condition ② |

**Table 2. The evolution stability conditions of system (I)**

| equilibrium points | number | conditions |
|--------------------|--------|------------|
| $(0, 1, 0)$        | condition ① | $(\alpha - \beta)B + D < 0$, $-\Delta Q + E < 0$, $(1 - 2x)N + F_x < 0$ |
| $(0, 1, 1)$        | condition ② | $(\alpha - \beta)(B \cdot A) - T < 0$, $K > 0$, $(1 - 2x)N + F_x < 0$ |
| $(1, 0, 0)$        | condition ① | $(\alpha - \beta)(B \cdot A) - T < 0$, $K > 0$, $(1 - 2x)N + F_x < 0$ |
| $(1, 0, 1)$        | condition ② | $(\alpha - \beta)(B \cdot A) - T < 0$, $K > 0$, $(1 - 2x)N + F_x < 0$ |
| $(1, 1, 0)$        | condition ② | $(\alpha - \beta)(B \cdot A) - T < 0$, $K > 0$, $(1 - 2x)N + F_x < 0$ |
| $(x^*, y^*, z^*)$  | condition ③ | $\lambda_1 < 0$, $\lambda_2 < 0$, $\lambda_3 < 0$ |
$\Lambda_1 - \Lambda_5$ are not shown in the paper.

5. Analysis of Evolutionary Game Model
In order to establish an effective environmental governance system, this paper focuses on points (0,1,1), (1,1,1) and ($x^*$, $y^*$, $z^*$) for three scenarios. Their evolutionarily stable conditions will be drawn evolutionary path and analyzed the sensitivity of parameter changes.

5.1 Scenario 1: High Fiscal Decentralization, Active Governance, Up-to Standard Pollution Control
From Table 3, it needs to satisfy condition $\mathbb{2}$ which is composed of three inequalities. From the first inequality $(\alpha - \beta)(B - A) - T < 0$, when the tax share difference is smaller than the transfer payment, the central government tends to choose high fiscal decentralization, which requires it to take into account the matching of income and expenditure and select a consistent strategy according to it. The second inequality $K > 0$, means, $\Delta t(Q - N) + t_0 Q - \theta N + F_c - H - \Delta c > 0$. The situation requires local governments to formulate strict local environmental protection tax regulations and collect environmental tax as high as possible, increase the economic penalties $F_c$ on the illegal emission of enterprises, make every effort to curb the damage $H$ on the ecological environment, and reduce the number of subsidies $\theta$. The third inequality $((1 - t)P - t_n + \lambda - \theta)N - F_c < 0$ requires the central government to formulate a higher comprehensive tax rate $t$, demands local governments to develop a higher environmental tax rate and increase the economic penalties $F_c$. Meanwhile, attention should be paid to reduce the difference between emission reduction costs and subsidies so as to prevent a large imbalance between them which will impose great pressure to enterprises.

This paper uses MATLAB R2018a software to carry out numerical simulation of the evolution process of the strategy adjustment. Initially, the probability of the high fiscal decentralization chosen by central government, active governance by local governments, and pollution reduction by enterprises was 0.3, 0.6, and 0.8 respectively. The parameters are then assigned as $\alpha=0.7$, $\beta=0.3$, $t=0.6$, $P=10$, $Q=10$, $N=1$, $T=25$, $F_c=5$, $t_r=0.5$, $c_h=10$, $c_r=2$, $R=10$, $H=30$, $\theta = \lambda = 0.5$, with an aim to guarantee the satisfaction of evolutionary stability condition $\mathbb{2}$. The specific evolution paths are shown in Figure 1. In the diagrams, the horizontal axis represents the passage of time, the vertical axis represents the strategy selection probability of each group, and the curve represents the evolution process of each player's behavior. It can be seen that as time goes on, the central government takes the lead in reaching an equilibrium point and choose a high fiscal decentralization strategy, local governments then achieve a balance at a relatively high speed and choose the active governance strategy, enterprises need a long process to reach the equilibrium point and begin their pollution dealing. When $t=1.5$, the three-party strategy reaches an equilibrium along the evolution path.

The evolution process is shown in figure 2.

Figure 2. The Equilibrium Point (0,1,1) and the Evolution Path
5.2 Scenario 2: Low Fiscal Decentralization, Active Governance, Up-to-standard Pollution Control

From Table 3, it must satisfy condition (5), which consists of three inequalities. From the first inequality $T-(\alpha-\beta) (B-A) < 0$, when the tax share difference is larger than the transfer payment, the central government tends to choose low fiscal decentralization, which requires it to take into account the matching of income and expenditure. The second inequality $K+S > 0$, that is, $\Delta t(Q-N)+\epsilon t-Q\theta N+F_t+T-(1-\beta)B-H\Delta c > 0$, this situation is similar to that under scenario 1, and the difference between transfer payments and revenue sharing local governments under high fiscal decentralization should be increased. The third inequality $(1-t)P_{-t}+\lambda-\theta)N-F_{c}-2F_{g} < 0$ is similar to the third inequality under scenario 1, and the fines $F_{g}$ should be increased so as to ensure the strict penalties.

Similarly, using MATLAB to numerically simulate the evolution of the three players’ strategy adjustment for scenario 2. Initially, the probabilities respectively remains unchanged. Except for $T$ and $H$ change into 20, the assignments for other parameters are the same as those for scenario 1.

The evolution process is shown in figure 3.

![Figure 3. The Equilibrium Point (1,1,1) and the Evolution Path](image)

5.3 Scenario 3: The three parties all make strategic choices with certain probabilities

Under this scenario, the three entities choose a strategy with certain probabilities. Using MATLAB software to conduct numerical simulation, we can visually represent the changes of parameters on the strategy choices of each party. In figure 4, the abscissa represents each parameter change interval, the vertical axis represents the strategy selection probability of each group, and the curve represents the evolution process of each subject’s behavior.

The parameter sensitivity analysis are shown in figure 4.

![Figure 4. Parameter Sensitivity Analysis under Scenario3](image)
Table 3 shows the direction and degree of influence of the parameter increase on the three-party strategy selection. The results are as follows:

i) Increasing local environmental tax rates and transfer payments, strengthening political constraints will help increase the proportion of the central government choosing low fiscal decentralization.

ii) Increasing the comprehensive tax rate, increasing the environmental supervision fines, increasing the local fiscal expenditures on environmental protection and emission reduction subsidies will help the central government to choose high fiscal decentralization.

iii) Expanding the gap of revenue sharing between governments, increasing local fiscal expenditures on environmental protection and corporate emission reduction subsidies, enhancing officials' political constraints will increase the willingness of the local governments and enterprises to carry out environmental governance, and help form an efficient environmental governance system.

6. Conclusions

By building a three-party evolutionary game model under different fiscal and taxation policy orientations, we have come to the following conclusions,

(1) Under the conditions of low fiscal decentralization, active governance, up-to-standard pollution control, local governments will arrive at equilibrium faster and the three parties will reach an effective and stable solution quicker. Under the scenario of high fiscal decentralization, active governance, up-to-standard pollution control, the central government will reach the equilibrium point at a faster rate, under both scenarios, the evolution of enterprises is the slowest.

(2) The efficiency of environmental governance system is promoted if we increase the environmental fiscal expenditures, give more subsidies to enterprises' emission reduction, strengthen the supervision of environmental protection and enhance political constraints on the government officials, as well as appropriately using administrative penalties and other types of methods.

Table 3 Parameter sensitivity analysis of System (I)

| Parameters | Central Government Ratio of Low Fiscal Decentralization | Local Governments Ratio of Active Governance | Enterprises Ratio of Active Participation |
|------------|--------------------------------------------------------|---------------------------------------------|------------------------------------------|
| t          | Significantly Negative                                 | Slightly Positive                           | Significantly Positive                   |
| T          | Significantly Positive                                 | Slightly Positive                           | Significantly Negative                   |
| ξ          | Significantly Negative                                 | Significantly Positive                      | Significantly Positive                   |
| F_x        | Slightly Negative                                     | Significantly Negative                      | Slightly Positive                        |
| F_r        | Significantly Positive                                 | Significantly Negative                      | Slightly Positive                        |
| Δ t        | Slightly Positive                                     | Slightly Negative                           | No Significant Influence                 |
| Δ c        | Significantly Negative                                 | Significantly Positive                      | No Significant Influence                 |
| θ          | Significantly Negative                                 | Significantly Positive                      | Slightly Positive                        |
| R          | Slightly Positive                                     | Significantly Positive                      | Slightly Positive                        |

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