Construction of evolutionary game model between actors and governance system in forest operation

Guangju Wang1, Renshan Xie1, Beibei Zhang1 and Jianzhou Yang1
1Fujian Agriculture and Forestry University College of Economics, Fuzhou, 350002, China

Corresponding author and e-mail: Jianzhou Yang, yjz300@fafu.edu.cn

Abstract. With the continuous development of evolutionary game theory, evolutionary game is widely used in various fields of society. This paper constructs the evolutionary game model of actors and governance system in forest resource operation and management, and analyzes the stability strategy of each break-even point of the game system. The results suggest that: (1) When the parameters meet the conditions \( C_5 > pC_4 + C_2 \) \( R + C_3 < pC_4 \), the evolutionary stability strategy of the game system is of (no protection, no regulation), which may lead to the continuous deterioration of forest resources; (2) When the parameters meet the conditions \( C_5 < pC_4 + C_2 \) \( R + C_3 > pC_4 \) \( C_5 < C_2 \), the evolutionary stability strategy of the game system is of (no protection, regulation), which is to strengthen the supervision mechanism and improve the consciousness of actors to protect forest resources; (3) When the conditions are satisfied \( C_5 < pC_4 + C_2 \) \( R + C_3 < pC_4 \), there is no evolutionary stability strategy in the game system.

1. Introduction
With the continuous development of evolutionary game theory, evolutionary game is widely used in various fields of society. In this study, evolutionary game model is applied to the field of forest resources. Based on the bounded rationality hypothesis, the actors and the governance system pursue the maximization of their own economic interests on the premise of not damaging the ecological environment in the forest operation scenario. The two parties into game take cooperative means which are constantly evolving and adjusted (Can LIU, 2020) to choose the optimal decision-making results according to different scenarios, in order to realize their own interests. The actors have strong motivation to seek the best action solution according to the actual conditions, in order to balance the forest ecological benefits and economic benefits. Under the dual constraints of resources and system, the actors and the governance system carry out the multiple dynamic game. The behaviors of the two parties to game are constantly adjusted and changed, and finally tend to be partial stability. Based on this, this paper constructs the evolutionary game model of actors and governance system in forest resource operation and management, and analyzes the stability strategy of each break-even point of the game system.
2. Basic assumptions and evolutionary game model construction

2.1. Basic assumptions of evolutionary game model

(1) The cooperative behavior strategies for the participation of actors and governance system include cooperative and non-cooperative behavior strategies. The non-cooperative behavior of the actors is manifested as pursuing the maximization of economic benefits while ignoring the maximum carrying capacity of the forest ecosystem in the process of forest operation, and then deviating from the goal of coordinated development of forest ecology and forestry economy; the non-cooperative behavior of governance system is manifested as lack of governance means and supervision mechanism in the face of forest destruction, forest degradation, deforestation and other issues. However, the cooperative behavior means that both sides take forest resources protection as the goal and pursue the maximization of economic benefits on the premise of giving priority to forest resources and environmental protection when choosing cooperative strategies.

(2) According to the cost-benefit theory, it is assumed that $R_1$ is the economic benefits for the participation of actors in forest operation and protection, including forest products and timber benefits; $R$ is the increased economic benefits for the participation of actors in forest operation without protection; $C_1$ is expressed as the input cost of actors participating in forest resource operation, including afforestation cost, tending cost, cutting cost, and productive input cost such as chemical fertilizer, pesticide and labor number used in forest operation; $C_2$ expressed as forest degradation, deforestation and other losses caused by the lack of management and supervision of forest operation by actors in the governance system; $C_3$ expressed as the economic losses caused by the reduction of output due to the strictly standardized use of chemical fertilizers and pesticides in the governance system by actors; $P$ expressed as the probability that the governance system will punish the actors for violating relevant regulations in forest operation, and the penalty is $C_4$, $C_5$ is expressed as the system and supervision cost formulated by the governance system to regulate the actors’ forest operation behavior, that is, the cost of conflict resolution mechanism (Lei SU, 2020). For example, the penalty for illegal cutting of trees, the transportation cost and labor cost of forest law enforcement team’s inspection of mountain farms, and the cost of forest property dispute prosecution.

| Project | Governance system (regulation) | Governance system (no regulation) |
|---------|-------------------------------|----------------------------------|
| Actors (protection) | $R_1-C_1-C_3$, $R_2-C_5$ | $R_1-C_1-C_3$, $R_2-C_2$ |
| Actors (no protection) | $R_1+R-C_1-pC_4$, $R_2+pC_4-C_5$ | $R_1+R-C_1$, $R_2-C_2$ |

2.2. Construction of evolutionary game model

It is assumed that the probability that the probability of Actor A choosing to participate in the cooperation of forest resources governance is $x$ ($0 \leq x \leq 1$), the probability that Actor A does not participate in the cooperation of forest resources governance is $1-x$; It is assumed that the probability that governance system chooses to participate in the cooperation of forest resources governance is $y$ ($0 \leq y \leq 1$), the probability that governance system does not participate in the cooperation of forest resources governance is $1-y$; According to the model hypothesis in Table 1, the repeated game process of forest resource governance cooperation strategy of the two parties under the condition of bounded rationality is simulated by using the replication dynamic equation. The model is as follows:
The expected benefits of the cooperation and non-cooperation in forest resource governance chosen by the actors are $U_1$ and $U_2$, and the average expectation is $\overline{U}$
\[
U_1 = y(R_1 - C_1 - C_3) + (1 - y)(R_1 - C_1 - C_5) = R_1 - C_1 - C_3
\]
\[
U_2 = y(R_1 + R - C_1 - pC_4) + (1 - y)(R_1 + R - C_1) = -ypC_4 + R_1 + R - C_1
\]
\[
\overline{U} = xU_1 + (1 - x)U_2 = -xC_3 - ypC_4 + R_1 + R - C_1 + xypC_4 - xR
\]
The expected benefits of the cooperation and non-cooperation in forest resource governance chosen by the governance system are $V_1$ and $V_2$, and the average expectation is $\overline{V}$
\[
V_1 = x(R_2 - C_3) + (1 - x)(R_2 + pC_4 - C_5) = R_2 + pC_4 - C_4 - xpC_4
\]
\[
V_2 = x(R_2 - C_2) + (1 - x)(R_2 - C_2) = R_2 - C_2
\]
\[
\overline{V} = yV_1 + (1 - y)V_2 = ypC_4 - yC_5 - xypC_4 + R_2 - C_2 + yC_2
\]
The evolutionary game replication dynamic equation of the probability $x$ of the actors choosing cooperation strategy with respect to time $t$ is as follows:
\[
F(x) = \frac{dx}{dt} = x(U_1 - \overline{U}) = x(x - 1)(C_3 + R - ypC_4)
\]
The evolutionary game replication dynamic equation of the probability $y$ of the governance system choosing cooperation strategy with respect to time $t$ is as follows:
\[
F(y) = \frac{dy}{dt} = y(V_1 - \overline{V}) = y(y - 1)(xpC_4 + C_5 - pC_4 - C_2)
\]
The replication dynamic equation of actors and governance system constitutes the game dynamic replication system.
\[
\begin{cases}
\frac{dx}{dt} = x(x - 1)(C_3 + R - ypC_4) = 0 \\
\frac{dy}{dt} = y(y - 1)(xpC_4 + C_5 - pC_4 - C_2) = 0
\end{cases}
\]
The equilibrium point of the system can be obtained as follows: $(0,0)$, $(1,0)$, $(0,1)$, $(1,1)$, $(\frac{pC_4+C_2-C_5}{pC_4}, \frac{C_3+R}{pC_4})$

3. Analysis on the stability strategy of the equilibrium point of game system
The stability of equilibrium points in evolutionary game system is analyzed by constructing Jacobian matrix. When the determinant of Jacobian matrix of equilibrium point is $\det J > 0$ and $\text{tr}J < 0$, the break-even point is locally stable.
\[
\det J = \begin{vmatrix}
\frac{\partial}{\partial x} \left( \frac{dx}{dt} \right) & \frac{\partial}{\partial y} \left( \frac{dx}{dt} \right) \\
\frac{\partial}{\partial x} \left( \frac{dy}{dt} \right) & \frac{\partial}{\partial y} \left( \frac{dy}{dt} \right)
\end{vmatrix} = \begin{vmatrix}
(2x - 1)(C_3 + R - ypC_4) & -x(x - 1)pC_4 \\
y(y - 1)pC_4 & (2y - 1)(xpC_4 + C_5 - pC_4 - C_2)
\end{vmatrix}
\]
\[
\text{tr}J = (2x - 1)(C_3 + R - ypC_4) + (2y - 1)(xpC_4 + C_5 - pC_4 - C_2)
\]
Table 2. Determinant of Jacobin matrix at each break-even point.

| Break-even point | $\det J$ |
|------------------|---------|
| $(0,0)$          | $(R + C_3)(C_5 - pC_4 - C_2)$ |
| $(0,1)$          | $(R + C_3 - pC_4)(pC_4 + C_2 - C_5)$ |
| $(1,0)$          | $(R + C_3)(C_2 - C_5)$ |
| $(1,1)$          | $(R + C_3 - pC_4)(C_2 - C_5)$ |
| $(pC_4 + C_2 - C_5, \frac{C_3 + R}{pC_4})$ | $(pC_4 + C_2 - C_5)(C_2 - C_5)(R + C_3)(R + C_3 - pC_4)$ |
|                  | $(pC_4)^2$ |

Table 3. Trajectory of Jacobin matrix at each break-even point.

| Break-even point | $\text{tr}J$ |
|------------------|--------------|
| $(0,0)$          | $-(R + C_3) - (C_5 - pC_4 - C_2)$ |
| $(0,1)$          | $-(R + C_3 - pC_4) - (pC_4 + C_2 - C_5)$ |
| $(1,0)$          | $(R + C_3) + (C_2 - C_5)$ |
| $(1,1)$          | $(R + C_3 - pC_4) - (C_2 - C_5)$ |
| $(pC_4 + C_2 - C_5, \frac{C_3 + R}{pC_4})$ | $0$ |

Table 4. Stability of break-even point.

| Break-even point | $\det J$ | $\text{tr}J$ | Stability   |
|------------------|---------|--------------|-------------|
| $(0,0)$          | +       | -            | Stable      |
| $(0,1)$          | +       | +            | Unstable    |
| $(1,0)$          | -       | Undetermined | Saddle point|
| $(1,1)$          | -       | Undetermined | Saddle point|
Table 5. Stability of break-even point.

| Break-even point | det $J$ | $trJ$   | Stability |
|------------------|---------|---------|-----------|
| (0,0)            | −       | Undetermined | Saddle point |
| (0,1)            | +       | −       | Stable    |
| (1,0)            | +       | +       | Unstable  |
| (1,1)            | −       | Undetermined | Saddle point |

Table 6. Stability of break-even point.

| Break-even point | det $J$ | $trJ$   | Stability |
|------------------|---------|---------|-----------|
| (0,0)            | −       | Undetermined | Saddle point |
| (0,1)            | −       | Undetermined | Saddle point |
| (1,0)            | +       | Undetermined | Saddle point |
| (1,1)            | +       | Undetermined | Saddle point |
| ($x^*,y^*$)      | 0       |         | Central point |

4. Discussion on the parameters of evolutionary stability strategy for game system

First of all, when the conditions $C_5 > pC_4 + C_2$ and $R + C_3 < pC_4$ are satisfied, the stability analysis results of each break-even point are shown in Table 4. The two parties to game evaluate the cost of policy formulation and implementation, so as to decide whether to implement the policy for regulation of the actors (Weihong CHEN, 2019). The key to improve forest protection is to improve the regulatory mechanism and forest protection related systems. The loss caused by the implementation of penalty or non-regulation of forest. No matter the organization or the society, a good system can prevent bad people from doing bad things, while a bad system can make good people become bad people. If the penalty is greater than the additional benefits increased for not protecting the forest, chemical fertilizer should be strictly used to enhance the awareness of actor for forest protection. The evolutionary stability strategy of the game system is (no protection, no regulation), which may lead to the continuous deterioration of forest resources.

Secondly, when the conditions $C_5 < pC_4 + C_2$, $R + C_3 > pC_4$ and $C_5 < C_2$ are satisfied, the stability analysis results of each break-even point are shown in Table 5. The evolutionary stability strategy of the game system is (no protection, regulation), improve the consciousness of actors to protect forest resources through the supervision mechanism.

Thirdly, when the conditions $C_5 < pC_4 + C_2$ and $R + C_3 < pC_4$ are satisfied, the stability analysis results of each break-even point are shown in Table 6, that is, there is no evolutionary stability strategy in the game system. It can be known through the replication dynamic system equation, $F'(x) = (2x - 1)(C_3 + R - ypC_4)$ when $y > y^*$, $F'(1) < 0$, $F'(0) > 0$, $x = 1$ is a stable strategy. At this time, the actors choose a stability strategy to support forest protection. The evolution phase diagram is shown in Figure 1 (a). When $y < y^*$, $F'(1) > 0$, $F'(0) < 0$, $x = 0$ is a stability strategy. At this time, actors choose a stability strategy that does not support forest protection. The
evolution phase diagram is shown in Figure 1 (b). Similarly, 
\[ F'(y) = (2y - 1)(xpC_4 + C_5 - pC_4 - C_2), \]
when \( x > x^* \), \( F'(0) < 0 \), \( F'(1) > 0 \), \( y = 0 \) is a stable strategy, that is, when the game system reaches a stable state, the governance system chooses to regulate the actors' stability strategy of forest protection, and the evolutionary phase diagram is shown in Figure 1 (c). When \( x < x^* \), \( F''(0) > 0 \), \( F'(1) < 0 \), \( y = 1 \) is a stable strategy, that is, when the game system reaches a stable state, the governance system chooses to regulate the actors' stability strategy of forest protection, and the evolutionary phase diagram is shown in Figure 1 (d). To sum up, the evolutionary phase diagram of the game system can be divided into four regions, as shown in Figure 2.

![Figure 1. Evolution phase diagram. Figure 2. Evolution phase diagram.](image)

5. Quantitative results with numerical value as reference
Based on the evolutionary game analysis of governance system and actors in forest resources, the quantitative results with numerical value as reference show that: (1) When the parameters meet the conditions \( C_5 > pC_4 + C_2 \) and \( R + C_5 < pC_4 \), the evolutionary stability strategy of the game system is (no protection, no regulation), which may lead to the continuous deterioration of forest resources; (2) When the parameters meet the conditions \( C_5 < pC_4 + C_2 \) and \( R + C_5 > pC_4 \) and \( C_5 < C_2 \), the evolutionary stability strategy of the game system is of (no protection, regulation), which is to strengthen the supervision mechanism and improve the consciousness of actors to protect forest resources; (3) When the conditions \( C_5 < pC_4 + C_2 \) and \( R + C_5 > pC_4 \) are satisfied, there is no evolutionary stability strategy in the game system.

The evolutionary game between actors and governance system will have a profound impact on the operation mode and governance effect of forest resources (Jiacheng ZHAO, 2020). In the forest operation scenario, the policy recommendations to improve the efficiency of forest operation are as follows: The first thing is to build a multi-party communication and multiple participation model of forest resources governance. The actors participate in the process of policy practice and consolidate the right resources of alliance groups. The second thing is to adhere to the strict ecological protection system and establish a conflict resolution mechanism. Peng CHEN and Yi XIE (2015) analyzed that the governance system cannot charge any fees in the mediation of forest right disputes, but also needs to invest a lot of money, and the total amount even exceeds the actual value of the object of the dispute. The third thing is to formulate the implementation plan of forest operation. Based on the requirements of governance system and the experience and effective information accumulated in the specific forest operation, the actors formulate the forest operation plan which is operable and consistent with the
development goal of the superior policy. The actors actively participate in the process of policy formulation and practice, which can improve the collective decision-making level.

References

[1] Weihong CHEN, Zijuan CAO, Xiaowei WANG. Game Analysis of Government Supervision and Forest Farmers Behavior in Forest Carbon Sequestration Reserve [J] Issues of Forestry Economics, 2019, 39(1): 80-85.

[2] Peng CHEN, Yi XIE, Wangxi WEI, et al. Study on Institutional Dilemma of Collective Forest Right Dispute Resolution and Countermeasures [J] Forestry Economics, 2015(06): 56-60.

[3] Can LIU. The Decentralization of Collective Forestland Tenure Reform in China Since the Reform and Opening-up from the Perspective of Evolutionary Game Theory [J]. Chinese Rural Economy, 2020(05): 21-38.

[4] Elinor Ostrom. Governing the Commons: The Evolution of Institutions for Collective Action [M]. Translated by Xunda YU, Xudong CHEN, Shanghai: Shanghai Translation Publishing House, 2012:1-277.

[5] Lei SU, Chen YUAN, Jun GUAN. Evolutionary Game Analysis of the Supply Stability of Forestry Carbon Sequestration [J]. Issues of Forestry Economics, 2020, 40(02): 122-128.

[6] Yiqing SU, Ming QIN, Yahua WANG. Impact of Land Transfer on Rural Collective Action Ability under the Background of Labor Outflow -- Study Based on the Framework of Social Ecosystem (SES) [J] Management World, 2020, 36(07): 185-198.

[7] Jiacheng ZHAO, Pei ZHANG, et al. Actor-Centred Power Theory in Forest Governance [J] Resources Science, 2020, 42(4): 636-648.