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Research on Optimization of Family Farm Operation Strategies and Incentive Mechanisms Based on Evolutionary Game Theory: A Perspective of Rural Revitalization

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Abstract. This study examines cooperation strategies between family farms and e-commerce enterprises under rural revitalization, constructing a tripartite evolutionary game model involving family farms, e-commerce enterprises, and local government to analyze equilibrium point stability, using sensitivity analysis and Matlab simulation. The system contains eight pure strategy equilibrium points, five being conditionally stable. Decision-making depends on relative net benefits; higher benefits drive strategy selection. Increasing central policy subsidies and reducing policy costs promote positive government evolution. Local government can accelerate positive evolution by widening the subsidy gap between family farms and e-commerce enterprises, as this gap significantly influences government decisions and proper adjustment enables steady progress toward ideal states. Higher cooperation benefits and lower cooperation costs encourage positive e-commerce enterprise evolution. Meanwhile, increased renovation benefits and reduced renovation costs facilitate positive family farm evolution. Finally, corresponding recommendations are proposed for each stakeholder.

Keywords: rural revitalization, family farm, e-commerce, evolutionary game

1. Introduction

Rural development is a global challenge, and for China, an agricultural powerhouse, rural revitalization is a top priority that the Communist Party highly prioritizes. The 19th National Congress in 2017 officially designated "three rural issues" as the Party's foremost task and launched rural revitalization strategies. In 2022, President Xi Jinping again emphasized comprehensive rural revitalization in the 20th National Congress report [1]. The 2023 Central Document No. 1 stressed that solving three rural issues remains the Party's central focus, requiring nationwide efforts to build foundations for socialist modernization [2].

2. Assumptions of evolutionary game model

This game differs from traditional game theory where participants are completely rational, as evolutionary game theory assumes bounded rationality among players who must undergo adaptive adjustment processes to reach optimal strategies [3]. The three participants are family farms, local government, and e-commerce enterprises. Family farms can decide to maintain current conditions or pursue structural upgrades based on their development status and external incentive policies. Structural upgrading means family farms divide farmland into specialized sections according to customer demands, transforming planned production into order-based production to maximize farmland productivity [4]. E-commerce enterprises can choose between ordinary procurement or deep cooperation. Ordinary procurement simply involves purchasing farm products for resale on existing platforms, while deep cooperation means establishing specialized agricultural product sales platforms through joint operation with farms. Local government decisions involve varying support levels, and changes in government support affect both farms and e-commerce enterprises [5]. The tripartite relationship is shown in Figure 1. Based on the above analysis, the following assumptions are proposed:

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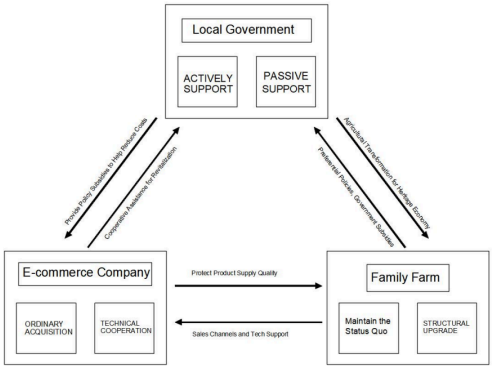

Figure 1. Game player relationship diagram

Assumption 1: Local government strategy choices are {active support, passive support}. When local government chooses active support, policy cost C occurs and central government subsidy P is received, with tax rate k for enterprises and farms. When local government chooses passive support, local tax rate k remains unchanged. ($0\leq k\leq 1$) ($P>C$)[3]

Assumption 2: E-commerce enterprise strategy choices are {deep cooperation, ordinary procurement}. When local government chooses active support, e-commerce enterprises choosing deep cooperation receive local government subsidy I1 and incur new platform construction operating cost CI1. When choosing ordinary procurement, they receive government subsidy I_2 ($I_1>I_2$) and incur logistics and procurement operating cost CI_2 ($CI_1>CI_2$). When local government chooses passive support, e-commerce enterprises receive only I_2 regardless of decision.

Assumption 3: Family farm strategy choices are {structural upgrade, maintain status quo}. When local government chooses active support, family farms choosing structural upgrade receive local government subsidy R1 and incur upgrade cost and production cost CR_1,

with local government obtaining public benefit A1. When choosing maintain status quo, they receive local government subsidy R_2 and incur production cost CR_2, with local government obtaining public benefit A2. When local government chooses passive support, family farms receive only R_2 regardless of decision. ($R_1>R_2$) ($CR_1>CR_2$) ($A_1>A_2$)

Assumption 4: When family farms choose structural upgrade and e-commerce enterprises choose deep cooperation, family farms obtain benefit C_1 and e-commerce enterprises obtain benefit B1 ($B_1>B_2$). In other cases, family farms obtain benefit C_2 and e-commerce enterprises obtain benefit B_2 ($C_1>C_2$).

Assumption 5: The probability of local government choosing active support is x ($0\leq x\leq 1$), and the probability of choosing passive support is 1-x. The probability of e-commerce enterprises choosing deep cooperation is y ($0\leq y\leq 1$), and the probability of choosing ordinary procurement is 1-y. The probability of family farms choosing structural upgrade is z ($0\leq z\leq 1$), and the probability of choosing maintain status quo is 1-z.

3. Establishment of evolutionary game model

Based on the assumed parameters, a benefit matrix of behavioral strategy combinations for local governments, e-commerce enterprises, and family farms is constructed, as shown in Table 1.

Table 1. Returns matrix of behaviora l strategy combination of local government, e-commerce enterprises and family farms

		E-commerce company	Family farm	
			Structural upgrade（z）	standstill （1-z）
local government	Actively support（x）	Deepen cooperation（y）	A_1+P-C-I_1-R_1+kB_1+kC_1 B_1-kB_1+I_1-C_{I1} C_1-kC_1+R_1-C_{R1}	A_2+P-C-I_1-R_2+kB_2+kC_2 B_2-kB_2+I_1-C_{I1} C_2-kC_2+R_2-C_{R2}
		ordinary acquisition（1-y）	A_1+P-C-I_2-R_1+kB_2+kC_2 B_2-kB_2+I_2-C_{I2} C_2-kC_2+R_1-C_{R1}	A_2+P-C-I_2-R_2+kB_2+kC_2 B_2-kB_2+I_2-C_{I2} C_2-kC_2+R_2-C_{R2}
	negative support（1-x）	Deepen cooperation（y）	A_1-I_2-R_2+kB_1+kC_1 B_1-kB_1+I_2-C_{I1} C_1-kC_1+R_2-C_{R1}	A2-I2-R2+kB2+kC2 B_2-kB_2+I_2-C_{I1} C_2-kC_2+R_2-C_{R2}
		ordinary acquisition（1-y）	A_1-I_2-R_2+kB_2+kC_2 B_2-kB_2+I_2-C_{I2} C_2-kC_2+R_2-C_{R1}	A_2-I_2-R_2+kB_2+kC_2 B_2-kB_2+I_2-C_{I2} C_2-kC_2+R_2-C_{R2}

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4. Policy stability analysis

The expected revenue of local government choosing "active support" is E_{x1}, then:

$$E_{X1} = yz(A_1 + P - C - I_1 - R_1 + KB_1 + KC_1) + y(1-z)(A_2 + P - C - I_1 - R_2 + kB_2 + kC_2) + (1-y)z(A_1 + P - C - I_2 - R_1 + kB_2 + kC_2) + (1-y)(1-z)(A_2 + P - C - I_2 - R_2 + kB_2 + kC_2) \quad (1)$$

The expected revenue of local government choosing "passive support" is Ex_2, then:

$$E_{x2} = yz(A_1 - I_2 - R_2 + KB_1 + KC_1) + y(1-z)(A_2 - I_2 - R_2 + kB_2 + kC_2) + (1-y)z(A_1 - I_2 - R_2 + kB_2 + kC_2) + (1-y)(1-z)(A_2 - I_2 - R_2 + kB_2 + kC_2) \quad (2)$$

The average expected revenue of local government is E_x, then:

$$Ex = xE_{X1} + (1-x)E_{X2} \quad (3)$$

The replication dynamic equation for local government strategy selection is F(x), then:

$$F(x) = dx/dt = x(E_{x1} - E_x) = x(1-x)(E_{x1} - E_{x2}) = x(1-x)(y(I_2 - I_1) + z(R_2 - R_1) + P - C) \quad (4)$$

$$F'(x) = (1-2x)(y(I_2 - I_1) + z(R_2 - R_1) + P - C) \quad (5)$$

According to the stability principle of differential equations, when local government strategy selection reaches stable state, F(x)=0 and F'(x)<0 must exist.

According to equations (1) to (4), let $y = \frac{z(R_2 - R_1) + P - C}{I_2 - I_1}$,, then the following situations exist:

When y=y*, F(x)=0 and F'(x)=0, stable strategy cannot be selected, x in [0,1] are all stable states, meaning whatever probability local government chooses "active support" or "passive support" are evolutionary stable strategies.

When y≠y*, let F(x)=0, then x=0 and x=1 both possibly become evolutionary stable points, representing local government's "active support" and "passive support" both possibly become evolutionary stable strategies.

The expected revenue of e-commerce enterprises choosing "deep cooperation" is E_{y1}, then:

$$E_{y1} = xz(B_1 - kB_1 + I_1 - C_{I1}) + x(1-z)(B_2 - kB_2 + I_1 - C_{I1}) + (1-x)z(B_1 - kB_1 + I_2 - CI_1) + (1-x)(1-z)(B_2 - kB_2 + I_2 - C_{I1}) \quad (6)$$

The expected revenue of e-commerce enterprises choosing "ordinary procurement" is E_{y2}, then:

$$E_{y2} = xz(B_2 - kB_2 + I_2 - C_{I2}) + x(1-z)(B_2 - kB_2 + I_2 - C_{I2}) + (1-x)z(B_2 - kB_2 + I_2 - C_{I2}) + (1-x)(1-z)(B_2 - kB_2 + I_2 - C_{I2}) \quad (7)$$

The average expected revenue of e-commerce enterprises is Ey, then:

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$$Ey = y\mathrm{E}_{y1} + (1-y)\mathrm{E}_{y2} \tag{8}$$

The replication dynamic equation for e-commerce enterprise strategy selection is F(y), then:

$$F(y) = dy/dt = y(\mathrm{E}_{y1} - \mathrm{E}_{y}) = y(1-y)(\mathrm{E}_{y1} - \mathrm{E}_{y2}) = y(1-y)(z(\mathrm{B}_1 - \mathrm{B}_2 + k\mathrm{B}_2 - k\mathrm{B}_1) + x(\mathrm{I}_1 - \mathrm{I}_2) + \mathrm{C}_{I2} - \mathrm{C}_{I1})$$

$$F'(y) = (1-2y)(z(\mathrm{B}_1 - \mathrm{B}_2 + k\mathrm{B}_2 - k\mathrm{B}_1) + x(\mathrm{I}_1 - \mathrm{I}_2) + \mathrm{C}_{I2} - \mathrm{C}_{I1}) \tag{10}$$

According to the stability principle of differential equations, when e-commerce enterprise strategy selection reaches stable state, F(y)=0 and F'(y)<0 must exist.

The expected revenue of family farms choosing "structural upgrade" is E_{z1}, then:

$$\mathrm{E}_{z1} = \mathrm{xy}(\mathrm{C}_1 - \mathrm{kC}_1 + \mathrm{R}_1 - C\mathrm{R}_1) + \mathrm{x}(1-\mathrm{y})(\mathrm{C}_2 - \mathrm{kC}_2 + \mathrm{R}_1 - C\mathrm{R}_1) + (1-\mathrm{x})\mathrm{y}(\mathrm{C}_1 - \mathrm{kC}_1 + \mathrm{R}_2 -$$

$$C\mathrm{R}_1) + (1-x)(1-y)(\mathrm{C}_2 - k\mathrm{C}_2 + \mathrm{R}_2 - C\mathrm{R}_1) \tag{11}$$

The expected revenue of family farms choosing "maintain status quo" is E_{z2}, then:

$$\mathrm{E}_{z2} = \mathrm{xy}(\mathrm{C}_2 - \mathrm{kC}_2 + \mathrm{R}_2 - C\mathrm{R}_2) + \mathrm{x}(1-\mathrm{y})\mathrm{C}_2 - \mathrm{kC}_2 + \mathrm{R}_2 - C\mathrm{R}_2) + (1-\mathrm{x})\mathrm{y}(\mathrm{C}_2 - \mathrm{kC}_2 + \mathrm{R}_2 -$$

$$C\mathrm{R}_2) + (1-x)(1-y)(\mathrm{C}_2 - k\mathrm{C}_2 + \mathrm{R}_2 - C\mathrm{R}_2) \tag{12}$$

The average expected revenue of family farms is Ez, then:

$$\mathrm{E}_z = z\mathrm{E}_{z1} + (1-z)\mathrm{E}_{z2} \tag{13}$$

The replication dynamic equation for family farm strategy selection is F(z), then:

$$\mathrm{F}(\mathrm{z}) = \mathrm{dz}/\mathrm{dt} = \mathrm{z}(\mathrm{E}_{z1} - \mathrm{E}_{z}) = \mathrm{z}(1-\mathrm{z})(\mathrm{E}_{z1} - \mathrm{E}_{z2}) = \mathrm{z}(1-\mathrm{z})(\mathrm{x}(\mathrm{R}_1 - \mathrm{R}_2) + \mathrm{y}(\mathrm{C}_1 - \mathrm{C}_2 + \mathrm{kC}_2 -$$

$$k\mathrm{C}_1) + C\mathrm{R}_2 - C\mathrm{R}_1) \tag{14}$$

$$F'(z) = (1-2z)(x(\mathrm{R}_1 - \mathrm{R}_2) + y(\mathrm{C}_1 - \mathrm{C}_2 + \mathrm{k}_{C2} - \mathrm{k}_{C1}) + \mathrm{C}_{C2} - \mathrm{C}_{C1}) \tag{15}$$

According to the stability principle of differential equations, when family farm strategy selection reaches stable state, F(z)=0 and F'(z)<0 must exist.

When x=x**, F(z)=0 and F'(z)=0, stable strategy cannot be selected, z in [0,1] are all stable states, meaning whatever probability family farms choose "structural upgrade" or "maintain status quo" are evolutionary stable strategies.When x≠x**, let F(z)=0, then z=0 and z=1 both possibly become evolutionary stable points, representing family farms' "structural upgrade" and "maintain status quo" both possibly become evolutionary stable strategies.

5. Stability analysis of equilibrium points in multi-actor evolutionary game systems

When subsidy gaps of both enterprises and farms cannot cover cost gaps, the system stabilizes at active support, ordinary procurement, maintain status quo. If enterprise subsidy gap exceeds cost gap but farm gap remains insufficient, equilibrium

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shifts to active support, deep cooperation, maintain status quo. Conversely, farms upgrade while enterprises maintain status quo [6,7]. When revenue gaps of both parties exceed cost gaps and government support costs surpass central subsidies, local government switches to passive support, forming equilibrium of passive support, deep cooperation, structural upgrade.

6. Conclusion

Players' strategy choices depend on relative net benefits, and higher net benefits lead to stronger preferences. Local government needs to increase central subsidies and compress policy costs to promote positive evolution. Reasonably widening subsidy gaps between family farms and e-commerce enterprises can drive smooth convergence, but blindly expanding gaps cannot achieve ideal evolution. E-commerce enterprises should enhance cooperation benefits and compress cooperation costs. Family farms need to increase renovation benefits and compress renovation costs. All parties jointly promote system convergence toward ideal stable state by improving strategy net benefits and compressing costs.

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