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Evolutionary Game Analysis of Solid Waste Emission Supervision under the Green Credit Policy

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Received: 12 August 2025; **Revised:** 11 November 2025; **Accepted:** 18 November 2025; **Published:** 25 November 2025

Abstract: Under the "dual carbon" targets, the governance of industrial solid waste emissions increasingly requires policy instruments that combine environmental enforcement with financial incentives. Existing green-credit studies mainly examine policy effects or static strategic equilibria, while paying limited attention to whether a regulatory game can endogenously converge when certification costs adjust with market participation. To address this gap, this paper develops a two-agent evolutionary game model between government regulators and solid-waste-emitting enterprises under a green credit policy. We first compare the strategic dynamics under a static certification cost and a dynamic certification cost mechanism. Theoretical analysis shows that, when certification cost is fixed, the interior equilibrium is only a center with periodic oscillations rather than an evolutionarily stable strategy, so the regulatory system lacks a self-stabilizing mechanism. By contrast, when certification cost rises with the proportion of enterprises applying for green credit, the Jacobian matrix at the interior equilibrium has a negative trace and a positive determinant, making the equilibrium asymptotically stable. This reveals a certification-cost-based convergence mechanism: dynamic verification costs can dampen strategic oscillations caused by subsidy dependence and greenwashing risk. Numerical simulation further confirms that penalties, supervision costs, emission-reduction costs, baseline certification costs, and green-credit operating returns jointly determine the stable adoption and supervision probabilities. The study contributes to the green credit and environmental regulation literature by transforming certification cost from an exogenous parameter into an endogenous stabilizing policy variable and by explaining how green credit can coordinate industrial emission control through both incentive and convergence effects.

Keywords: Green Credit; Evolutionary Game Theory; Simulation Analysis

1. Introduction

With the deepening advancement of the "dual carbon" goals, the supervision of industrial solid waste emissions has become a critical battleground for ecological civilization construction. According to the China Statistical Yearbook on Environment, China's industrial solid waste generation reached 4.1 billion tons in 2022, a year-on-year increase of 3.2%. The traditional "command-based" regulatory model suffers from diminishing marginal benefits due to frequent corporate evasion behaviors [1]. The green credit regulatory model is fundamentally different from traditional environmental regulation models. Green credit not only promotes technological innovation in enterprises by providing financial support and risk diversification but also plays a significant role in monitoring and

preventing pollution and promoting corporate green innovation. It has thus become a key institutional tool for facilitating the green transformation of development modes. Developing green credit to support corporate green innovation, thereby promoting the emission reduction process, is widely recognized as an effective pathway to achieving carbon neutrality goals [2]. To ensure that green credit effectively incentivizes enterprises to engage in green innovation and boosts the green transition of the economy, it is necessary not only to deeply examine its characteristics in corporate green innovation behavior and clarify its micro-level mechanisms but also to scientifically evaluate the effectiveness and efficiency of the implementation of related specific policies.

Prior studies on green credit generally fall into two main streams. The initial stream investigates the policy's implementation effects and underlying mechanisms, particularly their practical impact on pollution control and environmental governance. According to current research, there are two main ways that green credit policies might lower smog pollution: improving industrial structures and developing green technologies [3]. However, policy effectiveness is significantly moderated by firm heterogeneity. On one hand, green credit can enhance the green production efficiency of heavily polluting enterprises, with more pronounced effects observed in state-owned enterprises, large-scale firms, and those located in central and western regions. The underlying mechanisms include the financing scale effect and the financing cost effect [4]. On the other hand, such policies may initially inhibit green innovation in private, small-scale, and financially constrained firms, highlighting the critical moderating role of corporate financial resilience in policy response [5]. Additional investigation shows that although green credit can raise the overall factor productivity of businesses with high energy usage, its pollution and carbon reduction effects remain ambiguous [6]. This suggests that the policy's impact on environmental performance may involve complexity and time lags. Importantly, studies also show that green credit policies significantly promote carbon emission reduction in enterprises, with effects varying across regions and being particularly effective in reducing industrial emissions such as sulfur dioxide and soot. The long-term dynamic effects of these policies underscore the importance of sustained implementation for achieving environmental goals [7].

The second stream uses game-theoretic models to examine the strategic interactions among governments, enterprises, and financial institutions. Research indicates that well-designed reward-punishment mechanisms, especially penalty-centric approaches, can accelerate strategic convergence toward green credit adoption [8]. Enhanced policy enforcement and reduced compliance costs further motivate banks to implement green credit [9]. In sectoral contexts such as green building, the synergy between market willingness and policy incentives drives sustainable transformation even under marginal return disadvantages [10]. Empirically, green credit policies have proven effective in reducing corporate carbon emissions, particularly in polluting industries and state-owned sectors, with effects mediated through increased environmental investment and innovation [7]. Collectively, these findings underscore the importance of integrated policy design, strategic penalty deployment, and market-signaling mechanisms in fostering green credit ecosystems and supporting low-carbon transitions. Li et al. [11] focused on the "greenwashing" problem in green credit, analyzing how blockchain can inhibit "greenwashing" by enhancing information transparency and punishment mechanisms. Xu et al. [12] studied how green credit policies affect corporate green innovation behavior through technology spillover and market competitiveness mechanisms by constructing a tripartite evolutionary game model among banks, leading enterprises, and follower enterprises. Li et al. [13] further examined green credit from the perspective of carbon emissions trading by constructing a network evolutionary game model, showing that the interaction between financial constraints and carbon-market mechanisms can shape the strategic diffusion of green-credit behavior. Recent sustainable supply-chain studies also highlight that carbon constraints, trade credit, rebates, discounts, preservation technology, and green investment are increasingly integrated into operational decision-making models [14–16]. These studies broaden the low-carbon management literature by connecting financial arrangements with emission-control decisions.

In summary, green credit in China has achieved significant development, becoming an important policy tool for guiding capital towards green industries and restricting financing for highly polluting enterprises. Its scale continues to expand, the institutional framework is gradually improving, and environmental risk management is increasingly becoming central to bank credit decisions. However, a key challenge remains the need to strengthen the coordination mechanism between financial supervision and environmental law enforcement. This issue profoundly affects the strategic choices of enterprises facing green credit policies and how regulatory agencies can more effectively use credit leverage to enhance supervision efficiency. Therefore, deeply exploring the evolutionary game relationship among corporate solid waste emission behavior, bank credit strategies, and environmental supervision

enforcement under the green credit background holds significant theoretical and practical importance for optimizing policy combinations, improving regulatory efficiency, and promoting substantive environmental improvement in enterprises. The aforementioned research provides an important theoretical foundation for understanding the role of green credit in multi-agent collaborative environmental supervision. However, most literature still focuses on strategy stability and local equilibrium analysis, with insufficient discussion on the central convergence mechanism of the system and dynamic policy tools. Based on this, this paper introduces a dynamic certification cost mechanism, aiming to reveal the evolutionary stabilization mechanism of the strategic interaction between the government and enterprises under the green credit background, providing theoretical support and path references for improving solid waste emission supervision policies.

This paper focuses on solid waste emission supervision under green credit and asks three research questions. First, under a fixed green-credit certification cost, can the strategic interaction between government regulators and solid-waste-emitting enterprises converge to an evolutionarily stable strategy? Second, if certification cost is allowed to vary with the proportion of enterprises applying for green credit, can this dynamic cost mechanism transform an oscillatory system into a stable regulatory equilibrium? Third, how do penalty intensity, active supervision cost, emission-reduction cost, baseline certification cost, and green-credit operating return affect the stable probabilities of enterprise green-credit adoption and government active supervision?

Compared with prior research, this study has two advantages. First, it links green credit to the certification-cost channel, thereby clarifying how verification cost, subsidy withdrawal, and anti-greenwashing pressure affect enterprise choices. Second, it emphasizes the central convergence mechanism of the evolutionary system. The analysis shows that a fixed-cost setting produces periodic strategic oscillations, whereas a dynamic certification cost changes the trace of the Jacobian matrix and stabilizes the interior equilibrium. These findings extend the literature on green finance and environmental regulation by moving from static equilibrium identification to dynamic stabilization analysis.

The remainder of this paper is organized as follows. Section 2 presents the model assumptions and payoff structure. Section 3 constructs and analyzes the evolutionary game under static and dynamic certification cost mechanisms and verifies the convergence results through simulation. Section 4 discusses the implications of the study for academic research and industry practice. Section 5 concludes the paper and outlines limitations and future extensions.

2. Model Assumptions

H1. *The government (People's Bank of China, China Banking Regulatory Commission, Environmental Protection Department) and solid waste emission companies are the two players in the game. Businesses and the government both make boundedly reasonable strategic decisions* [17].

H2. *In the game model, the government can choose either Active Supervision (PI) or Negative Supervision (NI); solid waste emission enterprises can choose to apply for green credit projects to reduce solid waste emissions (GC) or maintain a high level of solid waste emissions (MP). That is, the government's strategy set is $\{PI, NI\}$, and the enterprise's strategy set is $\{GC, MP\}$. If the likelihood of a company selecting GC is x, then the likelihood of selecting MP is $1-x$. Accordingly, the likelihood that the government will select is y, and the likelihood that NI will be selected is $1-y$.*

H3. *For the government, choosing active supervision entails a supervision cost C_1* [18]*. In this case, all high-emission behaviors by enterprises are detected and subject to a corresponding fine F. Assume the supervision probability under negative government supervision is β. When the government supervises negatively, the supervision cost incurred is βC_1. In this case, only some high-emission behaviors are penalized, meaning the government's fine for high-emission behavior becomes βF. For enterprises, choosing GC requires incurring an emission reduction cost C_2* [18] *(which we also view as the principal for applying for green credit) and the certification cost P for applying for green credit projects* [19]*. When an enterprise chooses GC, it brings an environmental quality improvement benefit R_1 to the government. Simultaneously, the enterprise can obtain profit R_2 from using green credit for production and operation.*

In summary, we have defined the variables involved in the model (**Table 1**). Consequently, we also derive the payoff matrix for the game between solid waste emission enterprises and the government (**Table 2**).

Table 1. Notations explanation.

Parameters	Definitions
C_1	Government's active supervision cost
C_2	Enterprise's emission reduction cost
R_1	Government's benefit from environmental quality improvement
F	Government's penalty for enterprise's solid waste violation
R_2	Enterprise's profit from using green credit for operation
θ	Green credit interest rate
β	Supervision probability when government supervises negatively
P	Cost for enterprise to apply for green credit

Table 2. Payoff matrix.

		Enterprise	
		GC	**MP**
Government	PI	$-C_1 + R_1$ $R_2 - C_2(1+\theta) - P$	$-C_1 + F$ $-F$
	NI	$-\beta C_1 + R_1$ $R_2 - C_2(1+\theta) - P$	$-\beta C_1 + \beta F$ $-\beta F$

3. Model Construction and Analysis

3.1. Evolutionary Game Modelling of Government and Enterprise Behavior: The General Case

Let U_1 be the expected payoff for the government choosing PI (Positive Intervention), U_2 be the payoff for choosing NI (Negative Intervention), and $\bar{U}$ be the average payoff for the government. Based on **Table 2**, the government's payoffs are derived as follows:

$$\begin{cases} U_1 = x\left(-C_1 + R_1\right) + (1-x)\left(-C_1 + F\right) \\ U_2 = x\left(-\beta C_1 + R_1\right) + (1-x)\left(-\beta C_1 + \beta F\right) \\ \bar{U} = yU_1 + (1-y)U_2 \end{cases} \tag{1}$$

Let V_1 be the expected payoff for the enterprise choosing GC (Green Credit), V_2 be the payoff for choosing MP (Maintain Pollution), and $\bar{V}$ be the average payoff for the enterprise. Similarly, the enterprise's payoffs are:

$$\begin{cases} V_1 = R_2 - C_2(1+\theta) - P \\ V_2 = y(-F) + (1-y)(-\beta F) \\ \bar{V} = xV_1 + (1-x)V_2 \end{cases} \tag{2}$$

Equations (1) and (2) lead to the following replicator dynamics equations describing the evolution of the enterprise and government are obtained respectively as:

$$F(y) = \frac{dy}{dt} = y(1-y)(1-\beta)\left[(1-x)F - C_1\right] \tag{3}$$

$$F(x) = \frac{dx}{dt} = x(1-x)\left[R_2 - C_2(1+\theta) - P + yF + (1-y)\beta F\right] \tag{4}$$

Detailed derivations of the replicator equations are provided in **Appendix A**.

3.2. Discussion of the Model

Based on the above dynamic system, we can identify five distinct equilibrium points within this evolutionary game:

Proposition 1. *In the above evolutionary game model,*

(1) (0,0), (0,1), (1,0), and (1,1) represent the four boundary equilibria of the system.

(2) If $0 < \frac{F-C_1}{F} < 1$ *and* $0 < \frac{C_2(1+\theta)+P-\beta F-R_2}{(1-\beta)F} < 1$, *then* (x^*, y^*) *is also an equilibrium point, where*

$$(x^*, y^*) = (\frac{F - C_1}{F}, \frac{C_2(1+\theta) + P - \beta F - R_2}{(1-\beta)F})$$

Proof. At equilibrium, Equations (3) and (4) require $dy/dt = 0$ and $dx/dt = 0$. From Equation (3), $dy/dt = 0$ when $y = 0, y = 1$, or $(1-x)F - C_1 = 0$, which gives $x^* = (F - C_1)/F$. From Equation (4), $dx/dt = 0$ when $x = 0, x = 1$, or $R_2 - C_2(1+\theta) - P + \beta F + y(1-\beta)F = 0$, which gives $y^* = [C2(1+\theta) + P - \beta F - R2]/[(1-\beta)F]$.

Combining the boundary factors x in {0,1} and y in {0,1} gives the four boundary equilibria. Combining the two interior zero-payoff-difference conditions gives (x^*, y^*). The interior point is feasible only when both coordinates lie between 0 and 1. Therefore, Proposition 1 is proved.

Proposition 1 shows the equilibrium points of the evolutionary game model. Next, we investigate whether these points are ESS.

Corollary 1. *The stability analysis of the above equilibrium points is as follows:*

(1) The evolutionary game cannot reach an evolutionary stable strategy (ESS) at any of the four fixed equilibrium positions since they are all unstable.

(2) The central point (x^*, y^*) is also unstable.

Proof. According to Taylor and Jonker [20], the stability of the dynamic equations at equilibrium points can be analyzed. The Jacobian matrix of the system is:

$$J_1 = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} \end{bmatrix} = \begin{bmatrix} [R_2 - C_2(1+\theta) - P + yF + (1-y)\beta F](1-2x) & (1-\beta)F(1-x)x \\ -y(1-y)(1-\beta)F & (1-\beta)\left[(1-x)F - C_1\right](1-2y) \end{bmatrix}$$

The det J and trJ of the matrix at different equilibrium points are given in **Table 3**.

Table 3. The $detJ$ and trJ of five strategies.

Strategies	detJ	trJ
(0, 0)	$(R_2 - C_2(1+\theta) - P + \beta F)(1-\beta)(F - C_1)$	$R_2 - C_2(1+\theta) - P + \beta F + (1-\beta)(F - C_1)$
(0, 1)	$-(R_2 - C_2(1+\theta) - P + F)(1-\beta)(F - C_1)$	$R_2 - C_2(1+\theta) - P + F - (1-\beta)(F - C_1)$
(1, 0)	$(R_2 - C_2(1+\theta) + \beta F - P)(1-\beta)C_1$	$-(R_2 - C_2(1+\theta) + \beta F - P) - (1-\beta)C_1$
(1, 1)	$-(R_2 - C_2(1+\theta) - P + F)(1-\beta)C_1$	$-(R_2 - C_2(1+\theta) - P + F) + (1-\beta)C_1$
(x^*, y^*)	$\frac{(C_2(1+\theta) - \beta F - R_2 + P)(F - C_2(1+\theta) - P + R_2)(F - C_1)C_1)}{F^2}$	0

$detJ > 0$ and $trJ < 0$ are prerequisites for an evolutionarily stable strategy (ESS) [21]. As shown in **Table 3**, without given initial conditions regarding the relative relationships between parameters, there is insufficient evidence to determine whether the $detJ$ and trJ of the four strategies are greater than or less than zero, thus confirming part (1) of Corollary 1. The $detJ$ at the central point is > 0, indicating Lyapunov stability. Therefore, we should study the stability properties of point (x^*, y^*). If it is asymptotically stable, then (x^*, y^*) is an evolutionarily stable strategy.

The Jacobian matrix J_2 at the central point is:

$$J_2 = \begin{bmatrix} 0 & \frac{(1-\beta)(F - C_1)C_1}{F} \\ \frac{-(C_2(1+\theta) - \beta F - R_2 + P)(F - C_2(1+\theta) - P + R_2)}{(1-\beta)F} & 0 \end{bmatrix} \quad (5)$$

From the Jacobian matrix in Equation (5), we can obtain the eigenvalues λ_1, λ_2 at the central point, as shown in Equation (6).

$$\lambda_1, \lambda_2 = \pm i \sqrt{\frac{(F - C_1)C_1(C_2(1+\theta) - \beta F - R_2 + P)(F - C_2(1+\theta) - P + R_2)}{F^2}} \quad (6)$$

Part (2) of Corollary 1 is proven because(x^*, y^*) is not an evolutionarily stable strategy and is not asymptotically stable due to the purely imaginary eigenvalues of the Jacobian matrix at the central point.

From Corollary 1, it can be concluded that without adding initial conditions specifying the relative relationships between variables, the dynamic system does not have an evolutionarily stable strategy. That is, any minor change can influence the behavior of both enterprises and the government. Only by specifying some initial conditions can the evolutionarily stable strategy of the model be obtained.

Proposition 2. *Under different initial conditions, the evolutionary game model will possess different ESS.*

(1) When $F < C_1$ *and* $R_2 < -\beta F + C_2(1+\theta) + P$, $(0,0)$ *is an ESS.*
(2) When $F > C_1$ *and* $R_2 < -F + C_2(1+\theta) + P$, $(0,1)$ *is an ESS.*
(3) When $R_2 > -\beta F + C_2(1+\theta) + P$, $(1,0)$ *is an ESS.*
(4) Under no initial condition can $(1,1)$ *be an ESS.*

Proof. (1) On the boundary equilibria, the Jacobian matrix is triangular, so local stability is determined by its two diagonal eigenvalues. When $F < C_1$ and $R_2 < -\beta F + C_2(1+\theta) + P$, only at point $(0,0)$ are $detJ > 0$ and $trJ < 0$. That is, the government's regulatory cost exceeds the fine, and the profit from using green credit is less than the cost of emission reduction. Therefore, the government tends to regulate negatively, and enterprises choose not to reduce solid waste emissions. This situation is not conducive to emission reduction.

(2) When $F > C_1$ and $R_2 < -F + C_2(1+\theta) + P$, only at point $(0,1)$ are $detJ > 0$ and $trJ < 0$. That is, the government's regulatory cost is less than the fine, but the profit from using green credit is still less than the emission reduction cost. Therefore, the government tends to regulate actively, but high-emission enterprises continue to violate regulations. In this case, it is necessary to increase penalties for high-emission behavior to encourage enterprises to change their decisions.

(3) When $R_2 > -\beta F + C_2(1+\theta) + P$, only at point $(1,0)$ are $detJ > 0$ and $trJ < 0$. That is, the profit from choosing green credit exceeds the cost, so enterprises tend to choose green credit to reduce emissions, while the government in this case tends to regulate negatively.

(4) There are no parameter conditions that make $detJ > 0$ and $trJ < 0$ at point $(1,1)$. One eigenvalue is $\lambda y = (1-\beta)C1 > 0$, so the point is always unstable. Hence no parameter condition can make (1,1) an ESS. Proposition 2 is proved.

3.3. Analysis of the Evolutionary Game Model under the Dynamic Certification Cost Mechanism

As established in previous sections, under standard static conditions (i.e., with a fixed certification cost), the mixed-strategy equilibrium point of the evolutionary game model exhibits periodic oscillations. Due to the lack of an asymptotic stability mechanism, the model cannot naturally stabilize at the ideal strategy profile of (1,1). To break this structural instability and enable the system to converge, this paper proposes a dynamic green credit certification cost mechanism.

The core logic relies on the economic principles of subsidy degression and anti-greenwashing measures [22,23]. The certification cost for enterprises applying for green credit is no longer treated as a static variable, but rather adjusts dynamically in positive correlation with the proportion of enterprises choosing green credit. In the early phases of green credit promotion, the government assumes part of the verification burden through unified pre-certification and subsidies, thereby lowering the basic certification cost to incentivize market entry. However, as enterprise participation scales and the market matures, government subsidies are gradually phased out. Simultaneously, the influx of applicants increases the risk of 'greenwashing' [22,23] and loan fraud. Consequently, banks and regulators must enforce stricter thresholds and more rigorous investigations into corporate emission reduction measures, which inherently drives up the compliance and certification costs for the enterprises.

Mathematically, this dynamic mechanism is expressed as a linear function [24] of the enterprise participation rate:

$$P(x) = P_0 + kx \tag{7}$$

Where P_0 is the basic certification cost, the lower limit of certification cost. k is the sensitivity coefficient, with $0 < k < 1$.

The replication dynamic equations under the dynamic certification cost mechanism are obtained by substituting $P(x)$ into Equations (5) and (6):

$$F(y) = \frac{dy}{dt} = y(1-y)(1-\beta)\left[(1-x)F - C_1\right] \tag{8}$$

$$F(x) = \frac{dx}{dt} = x(1-x)\left[R_2 - C_2(1+\theta) - (P_0 + kx) + yF + (1-y)\beta F\right] \tag{9}$$

Proposition 3. *In the above evolutionary game model,*

(1) (0,0), (0,1), (1,0), and (1,1) are four fixed equilibrium points.

(2) If $0 < \frac{F-C_1}{F} < 1$ *and* $0 < \frac{P_0+kx+C_2(1+\theta)-\beta F-R_2}{(1-\beta)F} < 1$, *then* (x^*, y^*) *is also an equilibrium point, where*

$$(x^*, y^*) = \left(\frac{F - C_1}{F}, \frac{P_0 + kx + C_2(1+\theta) - \beta F - R_2}{(1-\beta)F}\right)$$

Proof. Similar to Proposition 1, let $F(x) = 0$, $F(y) = 0$, and $0 \le x \le 1$, $0 \le y \le 1$ to obtain the five equilibrium points. Proposition 3 is thus proved.

Proposition 3 gives five equilibrium points. As indicated by Corollary 2, we examine the stability of these five equilibrium points below:

Corollary 2. *The following is the stability study of the equilibrium points mentioned above:*

(1) All four fixed equilibrium points are unstable; the evolutionary game cannot achieve a stable evolutionary strategy (ESS) at these four points.

(2) The central point (x^*, y^*) *is an ESS.*

Proof. Lyapunov stability study indicates that the system's Jacobian matrix is as follows with the introduction of the dynamic certification cost mechanism:

$$J_3 = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} \end{bmatrix} = \begin{bmatrix} [R_2 - C_2(1+\theta) - P(x) + yF + (1-y)\beta F](1-2x) - k(1-x)x & (1-\beta)F(1-x)x \\ -y(1-y)(1-\beta)F & (1-\beta)\left[(1-x)F - C_1\right](1-2y) \end{bmatrix}$$

The determinant ($\det J$) and trace (trJ) of the matrix at different equilibrium points are given in **Table 4**. The Jacobian matrix at the center point is shown in Equation (10), and its eigen values are shown in Equations (11) and (12).

$$J_4 = \begin{bmatrix} -\frac{(F-C_1)C_1k}{F^2} & \frac{(1-\beta)(F-C_1)C_1}{F} \\ \frac{-(C_2(1+\theta)-\beta F-R_2+P(x))(F-C_2(1+\theta)-P(x)+R_2)}{(1-\beta)F} & 0 \end{bmatrix} \tag{10}$$

$$\lambda_3, \lambda_4 = -\frac{(F-C_1)C_1k}{2F^2} \pm i\frac{\sqrt{4(C_1-F)C_1F^2Q - [C_1(C_1-F)k]^2}}{2F^2} \tag{11}$$

$$Q = (C_2(1+\theta) - \beta F - R_2 + P(x))(F - C_2(1+\theta) - P(x) + R_2) \tag{12}$$

Table 4. The $detJ$ and trJ of five strategies.

Strategies	detJ	trJ
$(0,0)$	$(R_2 - C_2(1+\theta) - P(x) + \beta F)(1-\beta)(F-C_1)$	$R_2 - C_2(1+\theta) - P(x) + \beta F + (1-\beta)(F-C_1)$
$(0,1)$	$-(R_2 - C_2(1+\theta) - P(x) + F)(1-\beta)(F-C_1)$	$R_2 - C_2(1+\theta) - P(x) + F - (1-\beta)(F-C_1)$
$(1,0)$	$(R_2 - C_2(1+\theta) + \beta F - P(x))(1-\beta)C_1$	$-(R_2 - C_2(1+\theta) + \beta F - P(x)) + (1-\beta)C_1$
$(1,1)$	$-(R_2 - C_2(1+\theta) - P(x) + F)(1-\beta)C_1$	$-(R_2 - C_2(1+\theta) - P(x) + F) + (1-\beta)C_1$
(x^*, y^*)	$\frac{(C_2(1+\theta)-\beta F-R_2+P(x))(F-C_2(1+\theta)-P(x)+R_2)(F-C_1)C_1}{F^2}$	$-\frac{(F-C_1)C_1k}{F^2}$

The eigenvalues λ_3 and λ_4 in Equation (11) are a pair of complex eigenvalues with a real part, and the real part is less than 0. From this, it can be concluded that the center point is asymptotically stable, i.e., it is the ESS we aim to achieve. Therefore, the proof of Corollary 2 is established.

After introducing the dynamic certification cost mechanism, the evolutionary model will converge to (x^*, y^*). Next, we will analyze the influence of each variable on the position of (x^*, y^*).

Corollary 3. *Under the conditions* $0 < \frac{F-C_1}{F} < 1$ *and* $0 < \frac{P_0+kx+C_2(1+\theta)-\beta F-R_2}{(1-\beta)F} < 1$, *we can derive:*

(1) $\frac{\partial x^{\circ}}{\partial C_1} < 0, \frac{\partial x^{\circ}}{\partial F} > 0.$

(2) $\frac{\partial y^{\cdot}}{\partial F} > 0, \frac{\partial y^{'}}{\partial C_2} < 0, \frac{\partial y^{\circ}}{\partial R_2} < 0, \frac{\partial y^{'}}{\partial P_0} > 0.$

Proof. Based on the analysis in Proposition 3, we obtain the center point as:

$$(x^*, y^*) = (\frac{F - C_1}{F}, \frac{P_0 + kx + C_2(1+\theta) - \beta F - R_2}{(1-\beta)F})$$

It can be obtained by taking the first-order partial derivatives of x^* and y^* with respect to $C_1,\ F, R_2, C_2,\ and\ P_0$:

(1) $\frac{\partial x^{'}}{\partial C_1} = -\frac{1}{F} < 0$

(2) $\frac{\partial x^{*}}{\partial F} = \frac{C_1}{F^2} > 0$

(3) $\frac{\partial y^{\circ}}{\partial F} = -\frac{P_0+kx+C_2(1+\theta)-R_2}{(1-\beta)F^2} < 0$

(4) $\frac{\partial y^{*}}{\partial R_2} = \frac{-1}{(1-\beta)F} < 0$

(5) $\frac{\partial y^{*}}{\partial C_2} = \frac{1+\theta}{(1-\beta)F} > 0$

(6) $\frac{\partial y^{*}}{\partial P_0} = \frac{1}{(1-\beta)F} > 0$

Therefore, the proof of Corollary 3 is established.

Corollary 3 illustrates the impact of various variables on the strategies of the government and solid waste emission enterprises. The penalty F influences both the enterprise's and the government's decisions: a higher penalty increases both the probability of enterprises choosing green credit and the probability of the government actively supervising, indicating that substantial fines encourage enterprises to engage in green technological innovation and reduce direct solid waste emissions. The government's active supervision cost C_1 is negatively correlated with the probability of enterprises choosing GC. When government supervision costs are high, the government's willingness to supervise decreases, making enterprises more inclined to maintain high emissions. The base green credit certification cost P_0 is positively correlated with the probability of active government supervision. That is, when the initial certification cost is high, enterprises' enthusiasm for choosing GC diminishes, and reducing solid waste emissions relies more on government supervision. The principal cost C_2 required for enterprises to implement green credit projects is positively correlated with government supervision. When the cost for enterprises to implement green emission reduction projects is high, the probability of choosing GC decreases, thereby increasing the government's motivation to supervise.

3.4. Simulation Analysis of the Evolutionary Game Model for Solid Waste Emission Supervision

We used MATLAB 2024 to solve the differential equations and simulate the evolutionary trends. Since the primary purpose of the simulation is to visually demonstrate the dynamic evolutionary paths and verify the theoretical stability conditions, we adopt a baseline parameter assignment method commonly used in EGT literature [18,25]. The parameters are strictly set to satisfy the boundary conditions of the ideal equilibrium point. To ensure robust representation without loss of generality, we set the initial baseline parameters as follows: $C_1 = 3, \beta = 0.4$, $C_2 = 3.5, R_2 = 2, F = 9, P_0 = 2.5, k = 2, \theta = 0.25, T = 50$ [26]. It should be noted that the parameters used in the simulation are not measured in specific currency units or physical units. Since this study develops a theoretical evolutionary game model, all payoff-related parameters, including regulatory costs, emission reduction costs, penalties, certification costs, and operational benefits, are normalized into dimensionless payoff units. Therefore, the numerical assignments in the simulation represent relative magnitudes among different costs, benefits, and

policy incentives rather than directly observed monetary values. This normalization is commonly adopted in evolutionary game simulations because the main purpose is to verify the stability conditions and dynamic evolutionary trends derived from the theoretical model. The Simulation results are shown in **Figures 1–4**.

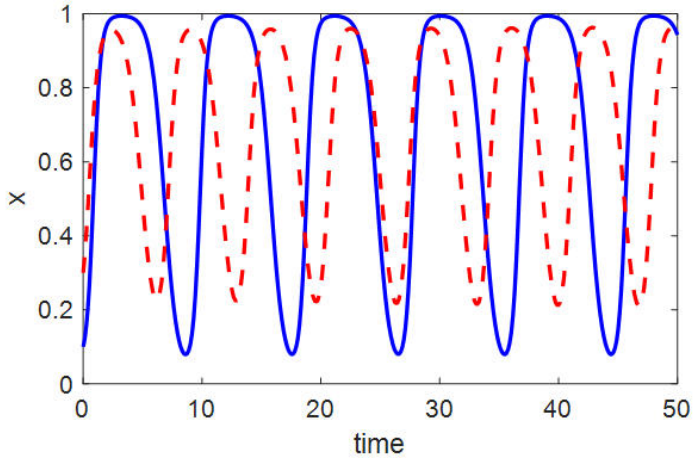


Figure 1. Evolutionary outcomes of enterprises choosing GC under general circumstance.

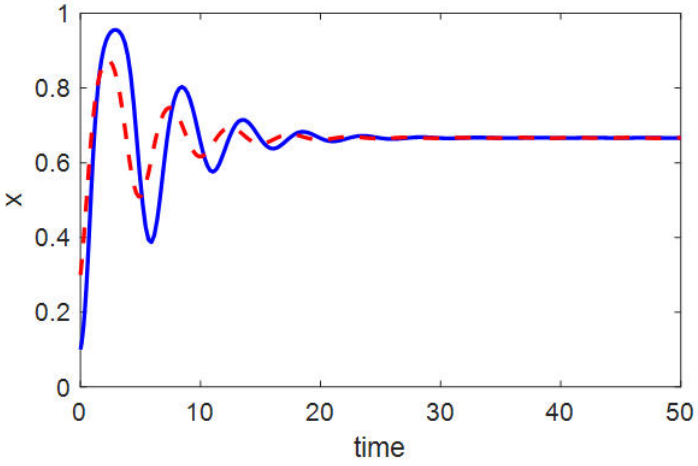


Figure 2. Evolutionary outcomes of enterprises choosing GC under a dynamic certification cost mechanism.

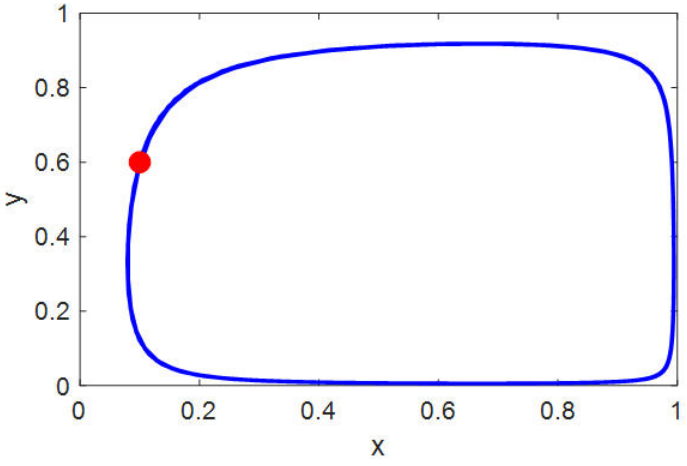


Figure 3. Behavioral Evolution Trajectory of Government and Enterprises under the Static Certification Cost Evolutionary Model.

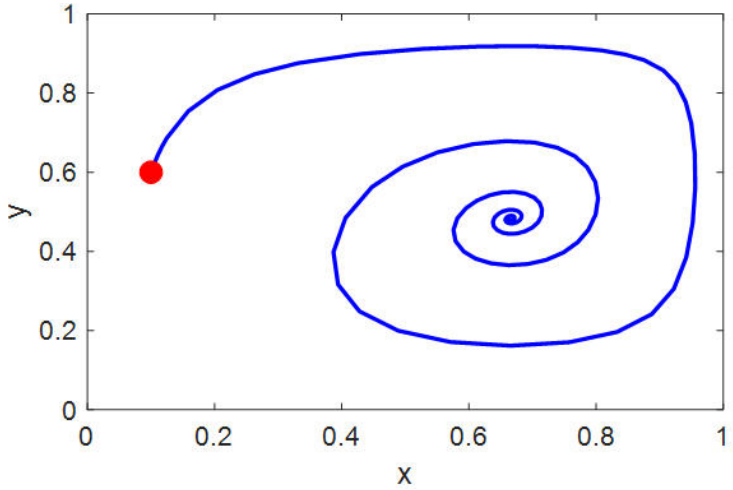


Figure 4. Game evolution trend between the government and solid waste emission enterprises under the dynamic certification cost mechanism.

We first solved for the proportion of enterprises choosing the GC strategy under the general scenario (static certification cost) over time with different initial values. **Figure 1** displays the outcome. The likelihood that manufacturers will select the GC strategy under a static carbon trading price with varying starting levels is shown in **Figure 1**. The initial probability of government active supervision is $y = 0.6$, $x = 0.1$ and $x = 0.3$ are two initial probabilities for the manufacturer choosing the GC strategy. In **Figures 1** and **2**, the solid line corresponds to the initial probability $x = 0.1$, while the dashed line represents $x = 0.3$. As shown in **Figure 1**, the probability of an enterprise choosing GC exhibits an evolutionary trend of periodic oscillation. It fails to converge to an evolutionarily stable point, meaning enterprises continuously adjust their strategies, which is not conducive to forming a stable emission reduction trend. Therefore, we incorporated the dynamic green credit certification cost mechanism into the simulation analysis to observe the changes in the proportion of enterprises choosing the GC strategy over time. **Figure 2** displays the outcome. **Figure 2** shows that the fluctuation amplitude of the likelihood of selecting GC steadily diminishes and moves towards a stable value as time grows under the dynamic certification cost mechanism.

We also examined how businesses and the government have changed their conduct. **Figure 3** shows the behavioral evolution trajectory of the government and enterprises under the general scenario.

As can be seen from **Figure 3**, under the initial condition $(x_0, y_0) = (0.1, 0.6)$, the evolution of the probability of enterprises choosing GC and the probability of the government actively supervising forms a closed orbital cycle around the initial point. Both enterprises and the government continuously change their optimal strategies without converging to a stable point. This indicates that under general circumstances, the government does not adjust its policies based on enterprise behavior, and both sides continuously adjust their strategies relying on financial incentives.

We explored the evolutionary game behavior of both parties under the dynamic certification cost mechanism with the initial value $(x, y) = (0.1, 0.6)$. **Figure 4** displays the outcome. **Figure 4** illustrates how the curve progressively approaches the center point as time progresses. This keeps the strategic choices of both parties in a relatively ideal steady state, which is conducive to achieving the goal of reducing solid waste emissions.

To further examine how key parameters affect the evolutionary outcomes of the solid waste emission supervision game under the dynamic certification cost mechanism, a parameter sensitivity analysis is conducted. Corollary 3 examined the influence of various variables on the strategies of the government and solid waste emission enterprises. Correspondingly, in the simulation analysis, by keeping other parameters constant, we systematically solved for the proportion of enterprises choosing green credit under different F and C_1 values, and the proportion of governments choosing active supervision under different F, R_2, C_2, and P_0 values, resulting in **Figures 5–10**.

Figures 5 and **6** show opposite responses to the penalty F for the two players. As F increases from 6 to 12, the stable enterprise GC probability rises from approximately 0.50 to 0.75, an increase of about 25 percentage points.

Over the same range, the stable government active-supervision probability falls from approximately 0.96 to 0.22. A stronger penalty therefore promotes enterprise adoption of green credit while reducing the equilibrium need for active government supervision. **Figure 7** shows the effect of the government's active-supervision cost C_1 on enterprises. When C_1 increases from 2 to 4, the stable enterprise GC probability decreases from approximately 0.78 to 0.56, a decline of about 22 percentage points. Higher supervision costs weaken the regulatory signal perceived by enterprises and consequently reduce their equilibrium willingness to choose green credit. **Figure 8** shows that a higher enterprise emission-reduction cost C_2 increases the government's equilibrium active-supervision probability. As C_2 rises from 2.5 to 4.5, the stable value of y increases from approximately 0.25 to 0.71. Costlier emission reduction makes voluntary enterprise adoption less attractive, so stronger government supervision is required at equilibrium.

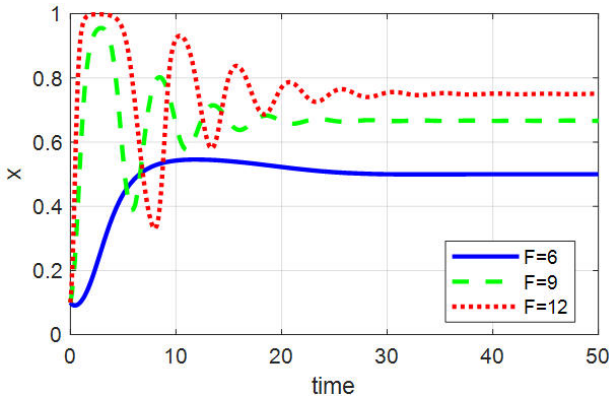


Figure 5. The percentage of businesses who select the GC approach in relation to various F values.

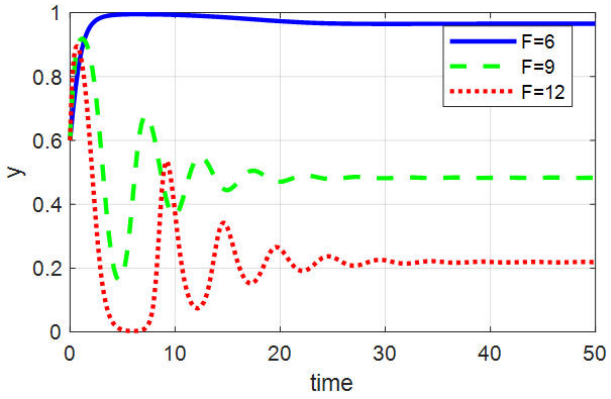


Figure 6. The percentage of governments who select the PI approach in relation to various F values.

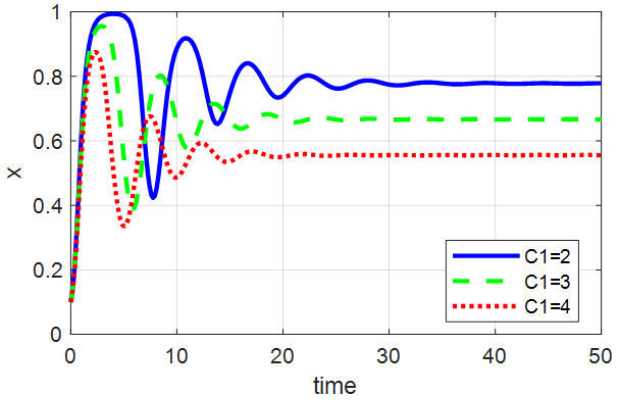


Figure 7. The percentage of businesses who select the GC approach in relation to various C_1 values.

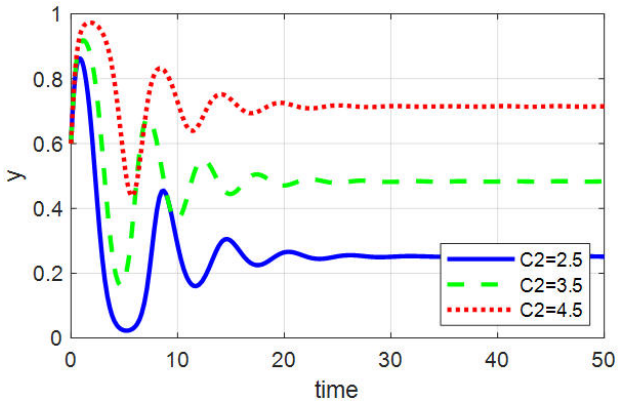


Figure 8. The percentage of governments who select the PI approach in relation to various C_2 values.

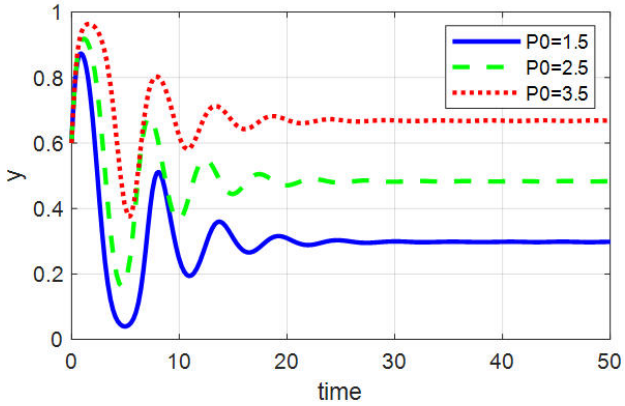


Figure 9. The percentage of governments who select the PI approach in relation to various P_0 values.

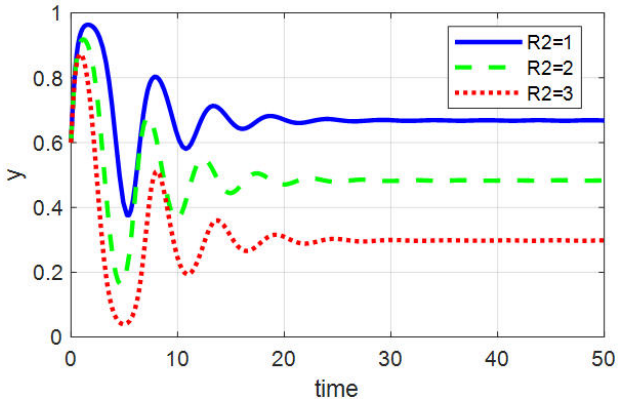


Figure 10. The percentage of governments who select the PI approach in relation to various R_2 values.

Figure 9 shows that increasing the baseline certification cost P_0 also raises the government's active-supervision probability. When P_0 increases from 1.5 to 3.5, the stable value of y rises from approximately 0.30 to 0.67, an increase of about 37 percentage points. A higher entry cost discourages voluntary green-credit participation and shifts more of the governance burden to active supervision.

Figure 10 shows that a higher operating return R_2 from using green credit reduces the equilibrium need for government intervention. As R_2 increases from 1 to 3, the stable government active-supervision probability declines from approximately 0.67 to 0.30. Greater private returns strengthen enterprises' incentive to adopt green credit voluntarily. The following policy suggestions are put out in light of the aforementioned research findings:

(1) Coordinate the use of the dynamic certification cost mechanism with existing policy tools such as environmental taxes, carbon trading, and green subsidies to form a triple policy force of "incentive-constraint-support," guiding enterprises from passive compliance to active emission reduction.
(2) Establish a green certification cost adjustment fund led by the government or industry associations, providing certification cost subsidies to small and medium-sized businesses as well as businesses undergoing a transformation, lowering their initial threshold for green transformation, and promoting more enterprises to participate in green credit projects.
(3) Establish information sharing and transparency enhancement mechanisms to reduce information asymmetry and increase the credibility of policy implementation.

4. Implications of the Study

4.1. Implications to Academic Research

This study contributes to academic research in three respects. First, it extends green credit research from policy-effect evaluation to strategic convergence analysis by showing how the dynamic adjustment of certification costs changes the stability of an evolutionary game. Second, it supplements existing low-carbon supply-chain and green-finance models [14–16] by identifying certification cost as a governance channel that links environmental verification, financial access, and anti-greenwashing enforcement. Third, the comparison between static and dynamic certification costs clarifies why some regulatory systems oscillate around mixed strategies and how an endogenous cost mechanism can act as a damping device.

4.2. Implications to the Industry

For regulators, the results suggest that green credit should not rely only on fixed subsidies or fixed certification thresholds. A phased certification-cost policy can lower early adoption barriers while gradually strengthening verification as participation expands. For financial institutions, the model emphasizes the need to improve information sharing, third-party certification, and anti-greenwashing review so that credit resources are directed to firms with genuine emission-reduction efforts. For enterprises, the findings show that green credit becomes attractive when the operating return from green transformation exceeds financing, certification, and emission-reduction costs; therefore, firms should integrate green credit with technological upgrading and solid-waste management rather than treating certification as a formal compliance procedure.

5. Conclusions

This research constructed an evolutionary game model between the government and solid waste emission companies under the green credit policy, analyzed the strategic interactions and equilibrium stability of both parties under static and dynamic certification cost mechanisms, and verified the theoretical results through simulation analysis. The main conclusions are as follows:

First, the game system between the government and businesses does not have an Evolutionarily Stable Strategy (ESS) in general, that is, when the certification cost is fixed. The strategies of both parties exhibit periodic oscillations and cannot converge to a stable state. Enterprises and the government continuously adjust their strategy choices, and the system behavior strongly depends on initial conditions.

Second, after introducing the dynamic certification cost mechanism, the system's center equilibrium point (x^*, y^*) becomes an asymptotically stable ESS. The outcomes of the simulation confirm the theoretical analysis's efficacy. Under the dynamic certification cost mechanism, the system can converge to a stable state more rapidly. This mechanism effectively suppresses the periodic fluctuations of the system, causing the government's active supervision probability and the enterprise's green credit project adoption probability to eventually converge to stable values, which is conducive to promoting the achievement of solid waste reduction goals.

Third, parameter sensitivity analysis shows that the government penalty amount F has a positive impact on the probability x of enterprises choosing green credit and a negative impact on the probability y of government active supervision. The government supervision cost C_1 and the enterprise emission reduction cost C_2 have negative and positive impacts on x and y, respectively. An increase in the green credit base certification cost P_0 enhances the necessity of government supervision but inhibits enterprises' enthusiasm for applying for green credit. R_2, the profit

derived from enterprise operations using green credit, negatively affects the likelihood of proactive government supervision, thus reducing the necessity for stringent regulation.

This study has several limitations that provide directions for future research. First, the model considers the government and enterprises as two players; future studies could explicitly include banks, certification agencies, and the public as additional strategic actors. Second, the model assumes a linear certification cost function; nonlinear, threshold-based, or data-driven certification cost mechanisms may better capture real-world verification processes. Third, information asymmetry and heterogeneous enterprises are not fully incorporated. Future research can combine evolutionary games with empirical data, network structures, or stochastic simulations to examine how green credit policies perform across regions, industries, and firm types.

In summary, this study emphasizes the significance of dynamic policy tools in stabilizing multi-party games and offers theoretical support for comprehending the mechanism of green credit in environmental governance. Future research could further consider the role of banks as a third party and strategic interactions under information asymmetry to more comprehensively characterize the application effectiveness of green credit in actual supervision.

Author Contributions

Conceptualization, F.S. and J.W.; methodology, J.W.; software, J.W.; formal analysis, J.W.; investigation, Z.Z.; resources, F.S.; writing—original draft preparation, J.W.; writing—review and editing, F.S., Z.Z. and J.W.; supervision, Z.Z. All authors have read and agreed to the published version of the manuscript.

Funding

This work did not receive any funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Acknowledgments

The authors would like to thank the editor and the anonymous reviewers for their valuable comments and detailed suggestions that have improved the presentation of this paper.

Conflicts of Interest

The authors declare no conflict of interest.

AI Use Statement

During the preparation of this manuscript, the authors used ChatGPT (OpenAI) solely for language refinement. No AI tools were used for data analysis, interpretation, or generation of scientific content. All outputs were critically reviewed and edited by the authors. The authors take full responsibility for the integrity and accuracy of the work.

Appendix A

Derivation of Equation (3):

The government replicator equation is:

$$dy/dt = y(U_1 - \overline{U})$$

According to the payoff functions of governments:

$$\begin{cases} U_1 = x(-C_1 + R_1) + (1-x)(-C_1 + F) \\ U_2 = x(-\beta C_1 + R_1) + (1-x)(-\beta C_1 + \beta F) \\ \bar{U} = yU_1 + (1-y)U_2 \end{cases}$$

$$dy/dt = y[U_1 - yU_1 - (1-y)U_2] = y(1-y)(U_1 - U_2)$$

$$U_1 - U_2 = x[(-C_1 + R_1) - (-\beta C_1 + R_1)] + (1-x)[(-C_1 + F) - (-\beta C_1 + \beta F)]$$

This simplifies to: $x[-(1-\beta)C_1] + (1-x)(1-\beta)(F - C_1) = (1-\beta)[(1-x)F - C_1]$
Therefore,

$$dy/dt = y(1-y)(1-\beta)[(1-x)F - C_1]$$

Derivation of Equation (4):
The enterprise replicator equation is:

$$dx/dt = x(V_1 - \overline{V})$$

According to the payoff functions of enterprises:

$$\begin{cases} V_1 = R_2 - C_2(1+\theta) - P \\ V_2 = y(-F) + (1-y)(-\beta F) \\ \bar{V} = xV_1 + (1-x)V_2 \end{cases}$$

$$dx/dt = x[V_1 - xV_1 - (1-x)V_2] = x(1-x)(V_1 - V_2)$$

$$V_1 - V_2 = R_2 - C_2(1+\theta) - P + yF + (1-y)\beta F$$

$$\frac{dx}{dt} = x(1-x)\left[R_2 - C_2(1+\theta) - P + yF + (1-y)\beta F\right]$$

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