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Investigating the Evolutionary Dynamics of Green Collaborative Innovation: A Four-Player Evolutionary Game Approach

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Highlights

How does this work link to systems science via contributions to systems practice, theory, and methodology?

- Develops a four-player evolutionary game framework integrating governments, universities, enterprises, and green financial institutions to reveal the dynamic interactions and feedback mechanisms within green collaborative innovation systems.
- Advances systems methodology by combining evolutionary dynamics, threshold analysis, and numerical simulation to examine how formal and informal institutional mechanisms shape multi-agent green transformation.

What are the main findings and/or the implications of the main findings?

- Identifies the key mechanisms driving green collaborative innovation, showing that enterprise transformation, technology commercialization, and financial governance jointly determine the evolution toward sustainable cooperation.
- Provides policy insights by demonstrating the importance of coordinated fiscal incentives, financial regulation, technology transfer mechanisms, and social supervision in promoting long-term green innovation.

Abstract

Green collaborative innovation is a complex socio-technical system involving interactions among governments, universities, enterprises, and financial institutions. However, existing studies often examine these actors separately or focus on bilateral relationships, limiting the understanding of how multi-agent strategies jointly evolve toward sustainable innovation. This study develops a four-player evolutionary game model incorporating regional governments, universities, local enterprises, and green financial institutions to investigate the dynamic evolution of green collaborative innovation under bounded rationality. The model integrates fiscal incentives, technology commercialization returns, financial constraints, reputation effects, and social advocacy mechanisms to explore the conditions under which collaborative strategies emerge and stabilize. Theoretical analysis identifies the evolutionary conditions of different strategic combinations, while numerical simulations examine how key factors influence the evolution process. The results reveal that enterprise deep green transformation plays a central role in shaping the evolution of the entire collaborative innovation system. Government subsidies and financial constraints jointly influence enterprises' transformation decisions, while technology commercialization returns and research support determine universities' incentives for green R&D. Green financial institutions contribute not only through capital provision, but also through environmental risk



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assessment and market-based governance. In addition, social advocacy indirectly affects the evolutionary process by influencing reputation-related incentives and strengthening institutional accountability. This study contributes to green innovation and systems science research by providing a multi-agent evolutionary framework that explains the interactions among policy, technology, finance, and institutional factors. The findings suggest that effective green collaborative innovation requires coordinated governance mechanisms that integrate fiscal support, financial regulation, technology transfer, and social supervision.

Keywords: green collaborative innovation; evolutionary game; sustainable transition

1. Introduction

Regions pursuing industrial upgrading are under growing pressure to reduce emissions and improve environmental performance. Green innovation is closely related to this process because it can generate economic value while reducing resource consumption and pollution. Compared with conventional technological innovation, however, green innovation has a stronger public-good attribute. Firms and research organizations usually bear the costs of R&D, technology upgrading, and commercialization, while part of the resulting knowledge spillovers and environmental benefits are shared by other actors. This “double externality” weakens the incentives of individual actors to invest in green technologies [1–3]. These features make green innovation difficult to achieve through the efforts of a single organization. Green technologies often involve long development cycles, large capital requirements, uncertain commercialization prospects, and coordination across research, production, regulation, and finance [4,5]. Local governments can provide policy guidance and institutional incentives; universities can supply knowledge and technological solutions; enterprises are responsible for technology application and industrial transformation; and financial institutions affect whether green projects can obtain stable and affordable capital. The effectiveness of green innovation therefore depends not only on the behavior of each actor, but also on whether their strategies can become compatible over time.

Studies on green collaborative innovation have examined this issue from several perspectives. Research on innovation ecosystems emphasizes that cooperation among governments, enterprises, universities, and research institutions can promote knowledge sharing, resource integration, and technology transfer [6–8]. Another stream of literature focuses on policy instruments, such as subsidies, environmental regulation, and performance assessment, and examines how these instruments influence firms’ green innovation decisions [9,10]. These studies explain why collaboration is needed and how institutional incentives may improve green innovation outcomes. However, much of the existing literature has given limited attention to the dynamic process through which collaboration is formed and stabilized. In practice, actors in a green innovation system do not make fixed decisions. Local governments may adjust subsidy intensity when fiscal pressure changes. Universities may reduce green R&D if the technology transfer returns are uncertain. Enterprises may remain at the level of passive compliance when transformation costs are high. Financial institutions may also revise credit conditions when environmental risks and default risks increase. These adaptive behaviors suggest that green collaborative innovation should be analyzed as an evolutionary process rather than as a static cooperation arrangement [11].

Evolutionary game theory provides a useful approach for studying such adaptive behavior. It has been applied to government–enterprise interactions under environmental regulation, government–enterprise–university cooperation in green innovation, and inter-governmental collaboration in regional carbon governance [12–15]. Recent studies have

further combined evolutionary game models with network structures or system dynamics to examine green supply chains, recycling innovation, and regional environmental governance [16–18]. Research on supply-chain collaboration and horizontal cooperation also shows that inter-organizational coordination matters for sustainability performance [19]. These studies offer useful insights into strategic interaction and evolutionary stability. Nevertheless, many existing evolutionary game models still place government intervention at the center of the analysis [20]. Enterprise green transformation is usually explained by fiscal subsidies, environmental penalties, or direct regulation. Financial institutions are often treated as external sources of capital, and their own strategic choices are rarely modeled explicitly. This treatment leaves an important mechanism underdeveloped. In the context of green finance, financial institutions do not simply provide funds. They screen green projects, assess environmental risks, adjust credit conditions, and restrict financing for environmentally risky borrowers. These actions can influence the cost of passive compliance and greenwashing behavior [21,22]. This point is important, because government subsidies and financial constraints operate through different channels. Subsidies can reduce the direct cost of green transformation, but excessive reliance on fiscal support may increase local government burdens and encourage subsidy-seeking behavior. Financial constraints, in contrast, can raise the cost of pollution-intensive production or passive compliance through risk premiums, stricter collateral requirements, reduced credit availability, and differentiated credit pricing. In this sense, green finance may work together with fiscal incentives rather than merely provide funding. The key question is how these two mechanisms interact and under what conditions they jointly encourage enterprises to undertake deep green transformation.

To examine this issue, this paper constructs a four-player evolutionary game model involving regional governments, universities, local enterprises, and green financial institutions. Regional governments choose between promoting green collaborative innovation and maintaining a traditional development orientation. Universities choose between strengthening green R&D and providing conventional technologies. Local enterprises choose between deep green transformation and passive compliance transformation. Green financial institutions choose between active green financial support and conventional credit services. In this study, active green financial support refers not only to the provision of green capital, but also to environmental screening, risk assessment, and differentiated credit arrangements. Based on these strategy choices, the paper derives the replicator dynamic equations, analyzes equilibrium stability, and conducts numerical simulations to examine how fiscal incentives, technology commercialization, enterprise transformation costs, and financial constraints affect system evolution.

This paper addresses three research questions. First, how does a green collaborative innovation system evolve when governments, universities, enterprises, and financial institutions adjust their strategies over time? Second, how does the strategic behavior of green financial institutions affect the stability of collaborative innovation? Third, under what conditions can government subsidies and financial constraints jointly induce enterprises to cross the cost threshold of deep green transformation?

This paper contributes to the literature in three ways. First, it extends existing evolutionary game research on green collaborative innovation by treating green financial institutions as strategic actors rather than as passive capital suppliers. This makes it possible to examine how credit screening, environmental risk assessment, and differentiated financing constraints influence the strategies of governments, universities, and enterprises. Second, the model clarifies the relationship between fiscal incentives and financial constraints. Prior studies have mainly emphasized government subsidies and environmental regulation as the main drivers of enterprise transformation. This paper shows that financial

constraints can complement fiscal incentives by increasing the cost of passive compliance. In particular, enterprise deep green transformation becomes more likely when the combined effect of government support and financial constraints is sufficient to offset the transformation cost. Third, the results provide more specific implications for regional green innovation governance. Instead of simply calling for stronger policy support, the model identifies several conditions that affect the stability of collaboration, including the cost of enterprise transformation, the intensity of fiscal subsidies, the strength of financial constraints, the returns from technology commercialization, and the risk-control cost of green finance. These conditions help explain why some green innovation systems move toward stable cooperation, while others remain trapped in passive compliance.

The remainder of this paper is organized as follows. Section 2 presents the problem description and basic assumptions of the four-player evolutionary game. Section 3 constructs the payoff matrix, derives the replicator dynamic equations, and analyzes the strategic evolution of each actor. Section 4 examines the stability of equilibrium points and conducts numerical simulations to explore the effects of key parameters on system evolution. Section 5 discusses the main findings, theoretical implications, policy implications, limitations, and future research directions.

2. Problem Description and Assumptions

Following the research questions proposed above, this section models the green collaborative innovation system as a four-population evolutionary game involving regional governments, universities, local enterprises, and green financial institutions. The model focuses on how these actors adjust their strategies according to changes in costs, benefits, risks, and policy incentives [23].

The four actors have different payoff structures. Regional governments obtain green development benefits when collaboration improves environmental performance, but they also bear policy coordination and subsidy costs. Universities may gain research funding and technology transfer income from green R&D while facing higher research costs and uncertainty. Local enterprises may benefit from market opportunities and policy support after deep green transformation, but transformation requires substantial investment. Green financial institutions may obtain policy incentives and reduce environmental credit risks through active green screening, but such screening increases review and monitoring costs. This study assumes that the four actors are boundedly rational. They do not identify the optimal strategy at the initial stage, but adjust their choices through repeated interaction, learning, and imitation. The evolutionary game framework is therefore used to describe how the probabilities of different strategies change over time.

The model applies mainly to regional green innovation systems in which four conditions are present. First, local governments have policy instruments such as subsidies, environmental regulation, and performance assessment. Second, universities or research institutions are able to provide green technologies that can be transferred to enterprises. Third, enterprises face meaningful costs when shifting from passive compliance to deep green transformation. Fourth, financial institutions have the capacity to conduct environmental risk assessment and apply differentiated credit conditions. These conditions are commonly found in green finance reform pilot zones, low-carbon city pilots, and regional green innovation clusters [24].

To construct a tractable evolutionary game model, the following assumptions are made.

Assumption 1. *Bounded rationality of actors.*

The green collaborative innovation system consists of four boundedly rational populations: regional governments, universities, local enterprises, and green financial institutions.

Due to technological uncertainty, incomplete information, policy adjustment costs, and market volatility, the actors cannot identify the payoff-maximizing strategy at the beginning of the game. Instead, they adjust their strategies through repeated observation, imitation, and trial-and-error learning. This assumption is consistent with the basic logic of evolutionary game theory and its applications in environmental governance and green innovation studies [25,26].

Assumption 2. *Strategy choices of the four actors.*

Regional governments choose between two strategies: promoting green collaborative innovation and maintaining a traditional development orientation. Let x denote the probability that regional governments promote green collaborative innovation, and $1 - x$ denote the probability that they maintain a traditional development orientation. Universities choose between strengthening green R&D and providing conventional technologies. Let y denote the probability that universities strengthen green R&D, and $1 - y$ denote the probability that they provide conventional technologies. Local enterprises choose between deep green transformation and passive compliance transformation. Let z denote the probability that local enterprises adopt deep green transformation, and $1 - z$ denote the probability that they adopt passive compliance transformation. Green financial institutions choose between active green financial support and conventional credit services. Let w denote the probability that green financial institutions provide active green financial support, and $1 - w$ denote the probability that they provide conventional credit services. Thus, $x, y, z, w \in [0, 1]$.

Assumption 3. *Government-related parameters.*

When a regional government promotes green collaborative innovation, it incurs the cost C_{gh} . This cost includes policy coordination, subsidy administration, cross-actor communication, project supervision, and the construction of green governance platforms. When the government maintains a traditional development orientation, it incurs the traditional governance cost C_{gl} , which reflects routine administrative management and conventional environmental governance. Since green collaborative innovation requires additional coordination and policy implementation, it is assumed that $C_{gh} > C_{gl}$.

If green collaboration improves regional environmental performance and supports industrial upgrading, the government obtains the macro-level green dividend M_g . This parameter captures the comprehensive benefits of green collaborative innovation, such as improved environmental quality, green industrial development, and enhanced regional competitiveness. This setting is consistent with studies showing that eco-innovation can generate both environmental benefits and policy-induced innovation effects [27]. When the government maintains a traditional development orientation, it may suffer the reputation and performance-assessment loss T_g . This loss may arise from ecological conflicts, public criticism, or higher-level environmental accountability. Similar assumptions have been used in studies of environmental regulation, government accountability, and regional green governance [26].

Assumption 4. *University-related parameters.*

When universities strengthen green R&D, they incur the high R&D cost C_{sh} , which includes personnel input, experimental expenditure, research time, and uncertainty in green technology development. When universities provide conventional technology, they incur the lower R&D cost C_{sl} . Since high-intensity green R&D requires more resources than conventional technology supply, it is assumed that $C_{sh} > C_{sl}$.

When local enterprises adopt deep green transformation, universities may obtain technology commercialization income W_u . This income may come from technology transfer,

patent licensing, technical consulting, or industry–university cooperation projects. This assumption is consistent with research on university–industry collaboration and technology transfer, which emphasizes that universities can contribute to innovation through knowledge commercialization and cooperation with firms [28].

When regional governments promote green collaborative innovation, universities may receive special research funding T_s . This parameter reflects government support for green R&D projects, collaborative innovation platforms, and low-carbon technology development. If universities provide only conventional technology, they may face the loss M_s , which represents reduced social recognition, missed collaboration opportunities, or weaker participation in green innovation networks. This setting reflects the fact that universities increasingly face evaluation pressures related to technology transfer, social contribution, and sustainability-oriented research outputs.

Assumption 5. *Enterprise-related parameters.*

Local enterprises are the main actors responsible for green technology application and commercialization. When enterprises adopt deep green transformation, they incur the transformation cost C_e . This cost includes green equipment investment, process upgrading, clean technology adoption, environmental management improvement, and organizational adjustment. Green transformation usually requires substantial investment and involves uncertain returns, which may weaken enterprises' willingness to transform without external incentives. When enterprises adopt deep green transformation, they may receive the government subsidy S_e . This parameter captures fiscal support, tax preferences, or policy rewards provided to enterprises that undertake substantive green upgrading. Such subsidies can reduce the direct cost burden of transformation.

If enterprises choose passive compliance transformation, they may avoid part of the transformation cost in the short run, but they may face financing constraints imposed by green financial institutions. This constraint is denoted by F_e . In this study, F_e does not mean that green financial institutions are encouraged to profit from punishment. Rather, it represents the combined effect of higher risk premiums, stricter collateral requirements, reduced credit availability, and differentiated credit pricing for environmentally risky or non-compliant borrowers. This setting is consistent with green credit policy and climate-related risk management, where banks are expected to identify, assess, monitor, and control environmental and social risks in lending decisions [29].

Assumption 6. *Green financial institution-related parameters.*

When green financial institutions provide active green financial support, they incur the high review cost C_{fh} . This cost includes environmental due diligence, green project identification, information verification, risk assessment, and post-loan monitoring. When they provide conventional credit services, they incur the lower routine review cost C_{fl} . Since active green financial support requires more information processing and risk-control efforts than conventional credit services, it is assumed that $C_{fh} > C_{fl}$.

When green financial institutions provide active green financial support, they may receive the government incentive S_f . This parameter reflects policy rewards, interest subsidies, risk compensation, or other incentives provided by governments to encourage green credit allocation and environmental risk screening.

When enterprises remain in passive compliance or engage in environmentally risky behavior, green financial institutions may face the climate-related bad debt risk N_f . This parameter captures potential default risks, asset quality deterioration, and credit losses associated with pollution-intensive or greenwashing projects. Active green financial support can reduce such risks through stricter screening, differentiated credit allocation, and post-loan monitoring. This assumption is consistent with the role of green finance in en-

vironmental risk assessment, credit screening, and the reallocation of financial resources toward greener firms [30].

Assumption 7. *Social advocacy and external governance pressure.*

The parameter k denotes the probability of social advocacy in the green collaborative innovation system. Social advocacy includes public supervision, media reporting, expert consultation, and participation by environmental NGOs or green industry associations. A higher k represents stronger external attention to ecological conflicts, green governance performance, and environmental information disclosure. Such advocacy increases the reputation and performance pressure faced by regional governments that maintain traditional development strategies and influences the reputation-related payoffs of universities providing conventional technologies [16]. In this model, social advocacy probability k is treated as an external institutional factor rather than an independent strategic player. It does not directly determine the strategic choices of enterprises or green financial institutions; instead, it affects the evolutionary process by modifying reputation-related payoffs and indirectly influencing multi-agent interactions.

The positive effect of social advocacy on local enterprises is denoted by H_e , including improved access to green resources, reputational gains, green product market recognition, and lower transaction costs in green technology application. The positive effect on green financial institutions is denoted by H_f , including better environmental information disclosure, improved project identification, higher-quality green assets, and lower greenwashing-related information asymmetry.

Based on these assumptions, the payoff matrix of the four-player evolutionary game is constructed, as shown in Table 1. The payoff structure captures the strategic interdependence among government incentives, university R&D, enterprise transformation, and green financial constraints.

Table 1. Payoff matrix of the four-player evolutionary game.

Strategy Choice		University	Green Financial Institution			
			Active Green Financial Support (w)		Conventional Credit Services ($1-w$)	
			Local Enterprise			
			Deep Green Transformation (z)	Passive Compliance Transformation ($1-z$)	Deep Green Transformation (z)	Passive Compliance Transformation ($1-z$)
Government	Green Collaboration (x)	Strengthening green R&D (y)	$T_g - C_{gh} - T_s - S_e - S_f$	$-C_{gh} - T_s - S_f$	$T_g - C_{gh} - T_s - S_e$	$-C_{gh} - T_s$
			$W_u + T_s - C_{sh}$	$T_s - C_{sh}$	$W_u + T_s - C_{sh}$	$T_s - C_{sh}$
			$B_e + S_e - C_e$	$B_e - F_e$	$B_e + S_e - C_e$	B_e
			$B_f + S_f - C_{fh}$	$B_f + S_f - C_{fh} + F_e$	$B_f - C_{fl}$	$B_f - C_{fl}$
	Conventional technology supply ($1-y$)	$T_g - C_{gh} - S_e - S_f$	$-C_{gh} - S_f$	$T_g - C_{gh} - S_e$	$-C_{gh}$	
		$-C_{sl} - (1-k)M_s$	$-C_{sl} - (1-k)M_s$	$-C_{sl} - (1-k)M_s$	$-C_{sl} - (1-k)M_s$	
		$B_e + S_e - C_e$	$B_e - F_e$	$B_e + S_e - C_e$	B_e	
		$B_f + S_f - C_{fh}$	$B_f + S_f - C_{fh} + F_e$	$B_f - C_{fl}$	$B_f - C_{fl}$	
Traditional Development ($1-x$)	Strengthening green R&D (y)	$-C_{gl}$	$-C_{gl} - (1-k)M_g$	$-C_{gl}$	$-C_{gl} - (1-k)M_g$	
		$W_u - C_{sh}$	$-C_{sh}$	$W_u - C_{sh}$	$-C_{sh}$	
		$-C_e - N_e + kH_e$	$-N_e + kH_e - F_e$	$-C_e - N_e + kH_e$	$-N_e + kH_e$	
		$-C_{fh} + kH_f$	$-C_{fh} + kH_f + F_e$	$-C_{fl} - N_f + kH_f$	$-C_{fl} - N_f + kH_f$	
Conventional technology supply ($1-y$)	$-C_{gl}$	$-C_{gl} - (1-k)M_g$	$-C_{gl}$	$-C_{gl} - (1-k)M_g$		
	$-C_{sl} - (1-k)M_s$	$-C_{sl} - (1-k)M_s$	$-C_{sl} - (1-k)M_s$	$-C_{sl} - (1-k)M_s$		
	$-C_e - N_e + kH_e$	$-N_e + kH_e - F_e$	$-C_e - N_e + kH_e$	$-N_e + kH_e$		
	$-C_{fh} + kH_f$	$-C_{fh} + kH_f + F_e$	$-C_{fl} - N_f + kH_f$	$-C_{fl} - N_f + kH_f$		

3. Evolutionary Game Model of Green Collaborative Innovation

Based on the assumptions and payoff structure described above, the expected payoffs and replicator dynamic equations of the four actors are derived below.

3.1. Regional Government Strategy

The expected payoffs of regional governments under green collaboration and traditional development are given by:

$$E_{11} = z(T_g - S_e) - yT_s - wS_f - C_{gh} \quad (1)$$

$$E_{12} = -C_{gl} - (1 - z)(1 - k)M_g \quad (2)$$

The average expected payoff of regional governments is:

$$F(x) = \frac{dx}{dt} = x(1 - x)[zT_g - yT_s - zS_e - wS_f - C_{gh} + C_{gl} + (1 - z)(1 - k)M_g] \quad (3)$$

Let:

$$H(x) = zT_g - yT_s - zS_e - wS_f - C_{gh} + C_{gl} + (1 - z)(1 - k)M_g \quad (4)$$

The derivative of $F(x)$ is:

$$\frac{dF(x)}{dx} = (1 - 2x)H(x) \quad (5)$$

According to the stability condition of evolutionary dynamics, the government strategy reaches an evolutionary stable state when:

$$F(x) = 0, \quad \frac{dF(x)}{dx} < 0$$

The critical threshold is obtained as:

$$z^{**} = \frac{yT_s + wS_f + C_{gh} - C_{gl} - (1 - k)M_g}{T_g - S_e - (1 - k)M_g} \quad (6)$$

where z^{**} denotes the critical threshold of the probability that local enterprises adopt deep green transformation.

Proposition 1. *The probability that regional governments adopt green collaboration depends on whether local enterprises achieve sufficient deep green transformation. Moreover, stronger university participation and stronger financial support increase the threshold required for governments to maintain green collaboration.*

Proof of Proposition 1. The sign of $H(x)$ determines the evolutionary direction of government strategy. Specifically, $x = 1$ is evolutionarily stable when $z > z^{**}$, whereas $x = 0$ becomes stable when $z < z^{**}$. The partial derivatives of z^{**} with respect to y and w are:

$$\frac{\partial z^{**}}{\partial y} = \frac{T_s}{T_g - S_e - (1 - k)M_g} > 0 \quad (7)$$

$$\frac{\partial z^{**}}{\partial w} = \frac{S_f}{T_g - S_e - (1 - k)M_g} > 0 \quad (8)$$

Therefore, increased university participation and stronger financial support raise the enterprise transformation threshold required for government green collaboration. $\square$

This result indicates that government willingness to sustain green collaboration depends on whether enterprise transformation can generate sufficient green returns to offset policy costs. Without effective enterprise transformation, fiscal support and coordination efforts may not produce the expected green development benefits.

3.2. University Strategy

The expected payoffs of universities under strengthening green R&D and conventional technology supply are given by:

$$E_{21} = zW_u + xT_s - C_{sh} \quad (9)$$

$$E_{22} = -C_{sl} - (1 - k)M_s \quad (10)$$

The average payoff of universities is:

$$F(y) = \frac{dy}{dt} = y(1 - y)[zW_u + xT_s - C_{sh} + C_{sl} + (1 - k)M_s] \quad (11)$$

Let:

$$H(y) = zW_u + xT_s - C_{sh} + C_{sl} + (1 - k)M_s \quad (12)$$

The derivative of $F(y)$ is:

$$\frac{dF(y)}{dy} = (1 - 2y)H(y) \quad (13)$$

According to the stability condition of evolutionary dynamics, the universities strategy reaches an evolutionary stable state when:

$$F(y) = 0, \quad \frac{dF(y)}{dy} < 0$$

The critical threshold is obtained as:

$$x^* = \frac{C_{sh} - C_{sl} - (1 - k)M_s - zW_u}{T_s} \quad (14)$$

where x^* denotes the critical threshold of the probability that regional governments promote green collaborative innovation in the evolution of the university's strategy.

Proposition 2. *The probability that universities strengthen green R&D is affected by enterprise technology demand and government research support. Higher technology commercialization returns and stronger enterprise transformation willingness reduce the government support threshold required for universities to adopt green R&D.*

Proof of Proposition 2. The sign of $H(y)$ determines the evolutionary direction of university strategy. Specifically, $y = 1$ is evolutionarily stable when $x > x^*$, whereas $y = 0$ becomes stable when $x < x^*$. The partial derivatives of x^* with respect to z and W_u are:

$$\frac{\partial x^*}{\partial z} = \frac{-W_u}{T_s} < 0 \quad (15)$$

$$\frac{\partial x^*}{\partial W_u} = \frac{-z}{T_s} < 0 \quad (16)$$

Therefore, higher enterprise transformation willingness and greater technology commercialization returns reduce the government support threshold required for universities to adopt green R&D strategies. $\square$

This result indicates that universities' green R&D decisions depend not only on government support, but also on whether technological outputs can be effectively transferred into industrial applications.

3.3. Local Enterprise Strategy

The expected payoffs of local enterprises under deep green transformation and passive compliance transformation are given by:

$$E_{31} = x(B_e + S_e) + (1 - x)(-N_e + kH_e) - C_e \quad (17)$$

$$E_{32} = xB_e + (1 - x)(-N_e + kH_e) - wF_e \quad (18)$$

The average payoff of local enterprises is:

$$F(z) = \frac{dz}{dt} = z(1 - z)[xS_e + wF_e - C_e] \quad (19)$$

Let:

$$H(z) = xS_e + wF_e - C_e \quad (20)$$

The derivative of $F(z)$ is:

$$\frac{dF(z)}{dz} = (1 - 2z)H(z) \quad (21)$$

According to the stability condition of evolutionary dynamics, the enterprise strategy reaches an evolutionary stable state when:

$$F(z) = 0, \quad \frac{dF(z)}{dz} < 0$$

The critical threshold is obtained as:

$$w^* = \frac{C_e - xS_e}{F_e} \quad (22)$$

where w^* denotes the critical threshold of the probability that green financial institutions provide active green financial support in the evolution of the local enterprise's strategy.

Proposition 3. *The probability that local enterprises adopt deep green transformation is jointly determined by government subsidies and financial constraints. Higher transformation costs increase the required financial constraint intensity, whereas stronger government subsidies reduce enterprises' dependence on financial constraints.*

Proof of Proposition 3. The sign of $H(z)$ determines the evolutionary direction of enterprise strategy. Specifically, $z = 1$ is evolutionarily stable when $w > w^*$, whereas $z = 0$ becomes stable when $w < w^*$. The partial derivatives of w^* with respect to C_e , x , and F_e are:

$$\frac{\partial w^*}{\partial C_e} = \frac{1}{F_e} > 0 \quad (23)$$

$$\frac{\partial w^*}{\partial x} = \frac{-S_e}{F_e} < 0 \quad (24)$$

$$\frac{\partial w^*}{\partial F_e} = \frac{-(C_e - xS_e)}{F_e^2} < 0 \quad (25)$$

Therefore, higher transformation costs increase enterprises' dependence on financial constraints, while stronger government subsidies reduce the financial pressure required to induce deep green transformation. $\square$

This result indicates that enterprise green transformation is determined by the combined effect of fiscal incentives and market-based financial mechanisms. Government subsidies can reduce direct transformation costs, while financing constraints increase the opportunity cost of passive compliance. Together, these mechanisms encourage enterprises to move toward deep green transformation.

3.4. Green Financial Institution Strategy

The expected payoffs of green financial institutions under active green financial support and conventional credit services are given by:

$$E_{41} = x(B_f + S_f) + (1-x)kH_f + (1-z)F_e - C_{fh} \quad (26)$$

$$E_{42} = xB_f + (1-x)(-N_f + kH_f) - C_{fl} \quad (27)$$

The average payoff of a green financial institution is:

$$F(w) = w(1-w)[xS_f + (1-x)N_f + (1-z)F_e - C_{fh} + C_{fl}] \quad (28)$$

Let:

$$H(w) = xS_f + (1-x)N_f + (1-z)F_e - C_{fh} + C_{fl} \quad (29)$$

The derivative of $F(w)$ is:

$$\frac{dF(w)}{dw} = (1-2w)H(w) \quad (30)$$

According to the stability condition of evolutionary dynamics, the green financial institution strategy reaches an evolutionary stable state when:

$$F(w) = 0, \quad \frac{dF(w)}{dw} < 0$$

The critical threshold is obtained as:

$$z^* = 1 - \frac{C_{fh} - C_{fl} - xS_f - (1-x)N_f}{F_e} \quad (31)$$

where z^* denotes the critical threshold of the probability that local enterprises adopt deep green transformation in the evolution of the green financial institution's strategy.

Proposition 4. *The evolution of green financial institutions' active support strategy is influenced by government incentives, climate-related risk exposure, and enterprise transformation progress. Higher government incentives, greater bad debt risks, and stronger financing constraints expand the probability space in which green financial institutions choose active support.*

Proof of Proposition 4. The sign of $H(w)$ determines the evolutionary direction of the green financial institution strategy. Specifically, $w = 1$ is evolutionarily stable when $z < z^*$, whereas $w = 0$ becomes stable when $z > z^*$. The partial derivatives of z^* with respect to S_f , N_f , and F_e are:

$$\frac{\partial z^*}{\partial S_f} = \frac{x}{F_e} > 0 \quad (32)$$

$$\frac{\partial z^*}{\partial N_f} = \frac{1-x}{F_e} > 0 \quad (33)$$

$$\frac{\partial z^*}{\partial F_e} = \frac{C_{fh} - C_{fl} - xS_f - (1-x)N_f}{F_e^2} > 0 \quad (34)$$

Therefore, stronger government incentives and stronger financing constraints increase the threshold z^* , thereby expanding the range of enterprise transformation levels under which green financial institutions maintain active support. $\square$

This result suggests that active green finance plays an important role during the transition stage of green innovation. When many enterprises remain exposed to environmental risks, financial institutions have stronger incentives to conduct green screening and provide differentiated financial services. As enterprises complete green transformation, the incentive for strict financial intervention gradually decreases.

3.5. Stability Analysis

To examine the evolutionary stability of the four-player green collaborative innovation system, the local stability of equilibrium points is analyzed by applying the Jacobian matrix method. Based on the replicator dynamic equations derived above, the Jacobian matrix of the system is expressed as:

$$J = \begin{bmatrix} J_{11} & J_{12} & J_{13} & J_{14} \\ J_{21} & J_{22} & J_{23} & J_{24} \\ J_{31} & J_{32} & J_{33} & J_{34} \\ J_{41} & J_{42} & J_{43} & J_{44} \end{bmatrix} = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z} & \frac{\partial F(x)}{\partial w} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z} & \frac{\partial F(y)}{\partial w} \\ \frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z} & \frac{\partial F(z)}{\partial w} \\ \frac{\partial F(w)}{\partial x} & \frac{\partial F(w)}{\partial y} & \frac{\partial F(w)}{\partial z} & \frac{\partial F(w)}{\partial w} \end{bmatrix}$$

According to Lyapunov's first method, an equilibrium point is locally asymptotically stable when all eigenvalues of the corresponding Jacobian matrix have negative real parts. The eigenvalues of the Jacobian matrix and the corresponding stability conditions of these equilibrium points are summarized in Table 2.

Table 2. Stability analysis of equilibrium points.

Equilibrium Point	Eigenvalues of Jacobian Matrix	Stability Condition
$E_1(0,0,0,0)$	$\lambda_1 = -C_{gh} + C_{gl} + (1-k)M_g$ $\lambda_2 = -C_{sh} + C_{sl} + (1-k)M_s$ $\lambda_3 = -C_e$ $\lambda_4 = N_f + F_e - C_{fh} + C_{fl}$	ESS if $N_f + F_e < C_{fh} - C_{fl}$
$E_2(1,0,0,0)$	$\lambda_1 = C_{gh} - C_{gl} - (1-k)M_g$ $\lambda_2 = T_s - C_{sh} + C_{sl} + (1-k)M_s$ $\lambda_3 = S_e - C_e$ $\lambda_4 = S_f + F_e - C_{fh} + C_{fl}$	Unstable
$E_3(0,1,0,0)$	$\lambda_1 = -T_s - C_{gh} + C_{gl} + (1-k)M_g$ $\lambda_2 = C_{sh} - C_{sl} - (1-k)M_s$ $\lambda_3 = -C_e$ $\lambda_4 = N_f + F_e - C_{fh} + C_{fl}$	Unstable
$E_4(0,0,1,0)$	$\lambda_1 = T_g - S_e - C_{gh} + C_{gl}$ $\lambda_2 = W_u - C_{sh} + C_{sl} + (1-k)M_s$ $\lambda_3 = C_e$ $\lambda_4 = N_f - C_{fh} + C_{fl}$	Unstable
$E_5(0,0,0,1)$	$\lambda_1 = -S_f - C_{gh} + C_{gl} + (1-k)M_g$ $\lambda_2 = -C_{sh} + C_{sl} + (1-k)M_s$ $\lambda_3 = F_e - C_e$ $\lambda_4 = -N_f - F_e + C_{fh} - C_{fl}$	Unstable

Table 2. Cont.

Equilibrium Point	Eigenvalues of Jacobian Matrix	Stability Condition
$E_6(1, 1, 0, 0)$	$\lambda_1 = T_s + C_{gh} - C_{gl} - (1 - k)M_g$ $\lambda_2 = -T_s + C_{sh} - C_{sl} - (1 - k)M_s$ $\lambda_3 = S_e - C_e$ $\lambda_4 = S_f + F_e - C_{fh} + C_{fl}$	Unstable
$E_7(1, 0, 1, 0)$	$\lambda_1 = -T_g + S_e + C_{gh} - C_{gl}$ $\lambda_2 = W_u + T_s - C_{sh} + C_{sl} + (1 - k)M_s$ $\lambda_3 = -S_e + C_e$ $\lambda_4 = S_f - C_{fh} + C_{fl}$	Unstable
$E_8(1, 0, 0, 1)$	$\lambda_1 = S_f + C_{gh} - C_{gl} - (1 - k)M_g$ $\lambda_2 = T_s - C_{sh} + C_{sl} + (1 - k)M_s$ $\lambda_3 = S_e + F_e - C_e$ $\lambda_4 = -S_f - F_e + C_{fh} - C_{fl}$	Unstable
$E_9(0, 1, 1, 0)$	$\lambda_1 = T_g - T_s - S_e - C_{gh} + C_{gl}$ $\lambda_2 = -W_u - C_{sh} + C_{sl} - (1 - k)M_s$ $\lambda_3 = C_e$ $\lambda_4 = N_f - C_{fh} + C_{fl}$	Unstable
$E_{10}(0, 1, 0, 1)$	$\lambda_1 = -T_s - S_f - C_{gh} + C_{gl} + (1 - k)M_g$ $\lambda_2 = C_{sh} - C_{sl} - (1 - k)M_s$ $\lambda_3 = F_e - C_e$ $\lambda_4 = -N_f - F_e + C_{fh} - C_{fl}$	Unstable
$E_{11}(0, 0, 1, 1)$	$\lambda_1 = T_g - S_e - S_f - C_{gh} + C_{gl}$ $\lambda_2 = W_u - C_{sh} + C_{sl} + (1 - k)M_s$ $\lambda_3 = -F_e + C_e$ $\lambda_4 = -N_f + C_{fh} - C_{fl}$	Unstable
$E_{12}(1, 1, 1, 0)$	$\lambda_1 = -T_g + T_s + S_e + C_{gh} - C_{gl}$ $\lambda_2 = -W_u - T_s - C_{sh} + C_{sl} - (1 - k)M_s$ $\lambda_3 = -S_e + C_e$ $\lambda_4 = -S_f - C_{fh} + C_{fl}$	Unstable
$E_{13}(1, 1, 0, 1)$	$\lambda_1 = T_s + S_f + C_{gh} - C_{gl} - (1 - k)M_g$ $\lambda_2 = -T_s + C_{sh} - C_{sl} - (1 - k)M_s$ $\lambda_3 = S_e + F_e - C_e$ $\lambda_4 = -S_f - F_e + C_{fh} - C_{fl}$	Unstable
$E_{14}(1, 0, 1, 1)$	$\lambda_1 = -T_g + S_e + S_f + C_{gh} - C_{gl}$ $\lambda_2 = W_u + T_s - C_{sh} + C_{sl} + (1 - k)M_s$ $\lambda_3 = -S_e - F_e + C_e$ $\lambda_4 = -S_f + C_{fh} - C_{fl}$	Unstable
$E_{15}(0, 1, 1, 1)$	$\lambda_1 = T_g - T_s - S_e - S_f - C_{gh} + C_{gl}$ $\lambda_2 = -W_u - C_{sh} + C_{sl} - (1 - k)M_s$ $\lambda_3 = -F_e + C_e$ $\lambda_4 = -N_f + C_{fh} - C_{fl}$	Unstable
$E_{16}(1, 1, 1, 1)$	$\lambda_1 = -T_g + T_s + S_e + S_f + C_{gh} - C_{gl}$ $\lambda_2 = -W_u - T_s - C_{sh} + C_{sl} - (1 - k)M_s$ $\lambda_3 = -S_e - F_e + C_e$ $\lambda_4 = -S_f + C_{fh} - C_{fl}$	ESS if $S_e + F_e > C_e$

As shown in Table 2, under the above realistic constraints, the replicator dynamic system has two pure-strategy evolutionarily stable strategies: $E_{16}(1, 1, 1, 1)$ and $E_1(0, 0, 0, 0)$.

Specifically, $E_{16}(1, 1, 1, 1)$ represents the optimal collaborative state in which the regional government promotes green collaboration, universities strengthen green R&D, local enterprises adopt deep green transformation, and green financial institutions provide active financial support. This equilibrium can be achieved when ecological dividends can be realized and technology commercialization channels function effectively. Under this strategy profile, the regional green collaborative innovation ecosystem reaches a Pareto-improving

state, generating the highest level of value co-creation and ecological synergy among the four players. However, the stability of $E_{16}(1, 1, 1, 1)$ requires the condition $S_e + F_e > C_e$. This implies that when fiscal subsidies from the regional government and financial constraints imposed by green financial institutions jointly generate sufficient pressure and incentives, and when this combined effect exceeds the intrinsic cost of deep green transformation, local enterprises are more likely to strengthen green technological upgrading and choose deep green transformation. Conversely, if government subsidies decline or financial regulatory pressure weakens, the replicator dynamic system may deviate from the optimal collaborative state.

When $N_f + F_e < C_{fh} - C_{fl}$, the stable strategy is $E_1(0, 0, 0, 0)$. This equilibrium indicates a low-collaboration state in which regional governments maintain a traditional development orientation, universities lack incentives for green R&D, local enterprises adopt passive compliance transformation, and green financial institutions return to conventional credit services. Under this strategy profile, the regional green collaborative innovation structure fails to function effectively because collaborative and regulatory behaviors are largely absent among the major actors. The system may therefore fall into a pollution lock-in state. To prevent this undesirable outcome, central or higher-level environmental authorities should strengthen top-level supervision and green finance certification standards, thereby increasing the implicit reputation losses and non-compliance costs associated with inaction within the system.

4. Numerical Simulation

4.1. Parameter Setting

The numerical simulation requires appropriate parameter settings to examine the evolutionary dynamics of the four-player system. Since this study aimed to reveal the strategic evolution mechanism rather than estimate empirical parameters, the baseline values were not directly calibrated from the observed monetary data. Instead, the parameters were normalized according to their relative economic relationships and theoretical conditions derived from the evolutionary model.

The parameter settings follow three principles. First, the relative magnitude among parameters reflects realistic decision-making conditions in green collaborative innovation. For example, enterprise green transformation usually requires substantial investment in equipment upgrading, process adjustment, technology adoption, and organizational restructuring. Therefore, the transformation cost C_e is set higher than the direct government subsidy S_e , indicating that fiscal incentives alone may not fully offset the transformation burden faced by enterprises. Second, the parameter values are consistent with the incentive and constraint mechanisms embedded in the model. Government subsidies S_e and financial constraints F_e jointly influence enterprise transformation decisions. A moderate subsidy level alone may not induce deep transformation, while excessive financial pressure may negatively affect enterprise liquidity and innovation capacity. Therefore, the baseline values were selected to represent a balanced policy environment rather than an extreme intervention scenario. Third, the parameter settings are consistent with the economic mechanisms identified in previous studies. Green innovation is characterized by high investment requirements, uncertainty, and positive externalities, which justify the inclusion of transformation costs, government incentives, and market-based financial constraints. Green finance mechanisms also emphasize environmental risk assessment, differentiated credit allocation, and risk control, supporting the inclusion of parameters related to financial incentives and bad debt risks.

The baseline values of the main parameters are presented in Table 3. For example, the enterprise transformation cost was set as $C_e = 22$, which is higher than the direct subsidy

$S_e = 12$. This setting reflects the practical situation that enterprises need to undertake additional expenditures beyond government support when implementing deep green transformation. The technology commercialization return $W_u = 12$ represents the economic value generated through university–industry technology transfer, while $T_s = 10$ reflects government research funding supporting green technology development. For green financial institutions, the active green support cost C_{fh} was set higher than the conventional credit service cost C_{fl} , because active green finance requires additional procedures, including environmental assessment, project screening, and risk monitoring. The government incentive S_f reflects policy support for financial institutions participating in green finance, while N_f captures potential bad debt risks associated with environmentally risky projects.

Table 3. Baseline parameter settings.

Symbol	Economic Meaning	Baseline Value	Setting Rationale
C_{gl}/C_{gl}	Cost of green collaboration/traditional governance	15/5	Green collaboration requires additional coordination and implementation costs
T_g	Macro-level green dividend generated by collaboration	45	Represents regional economic and environmental benefits
M_g	Government reputation loss from inaction	10	Represents external governance pressure
C_{sh}/C_{sl}	Cost of green R&D/conventional technology	20/5	Green R&D requires higher investment and uncertainty tolerance
W_u/T_s	Technology commercialization return/government research funding	12/10	Reflects university–industry transfer and public support
M_s	University reputation loss from conventional R&D	10	Represents reduced participation in green innovation networks
C_e	Enterprise deep green transformation cost	22	Higher than subsidy because transformation requires additional investment
S_e/F_e	Enterprise subsidy/financing constraint	12/15	Represents combined fiscal incentive and market discipline
C_{fh}/C_{fl}	Active green review cost/conventional credit cost	10/4	Green finance requires additional screening and monitoring
S_f/N_f	Financial institution incentive/bad debt risk	8/8	Represents policy support and credit risk

The initial strategy probabilities were set as:

$$x_0 = y_0 = z_0 = w_0 = 0.5$$

This setting represents a neutral initial condition in which none of the four actors has an ex ante strategic advantage. The subsequent evolutionary trajectory is therefore determined by the payoff differences among alternative strategies rather than by predetermined preferences.

4.2. Effects of Initial Strategy Probabilities

Initial strategy probabilities reflect the initial willingness of different actors to participate in green collaborative innovation. To examine the influence of initial conditions on evolutionary trajectories, one actor's initial probability was varied while the initial probabilities of the other actors were fixed at 0.5. Three initial states (0.2, 0.5, and 0.8) were considered to represent low, medium, and high initial willingness, respectively.

4.2.1. Effect of Initial Government Collaboration Probability

Figure 1a shows the effect of initial government collaboration probability (x_0) on the evolutionary trajectories. The results show that a higher initial government collaboration probability accelerates the evolution of universities, enterprises, and green financial institutions toward cooperative strategies. This indicates that government willingness plays an important role in initiating coordination among different actors. The reason is that regional governments provide policy guidance, financial support, and institutional coordination during the early stage of green innovation collaboration. A stronger initial willingness to cooperate improves the expectations of other actors and facilitates the formation of a stable collaborative system.

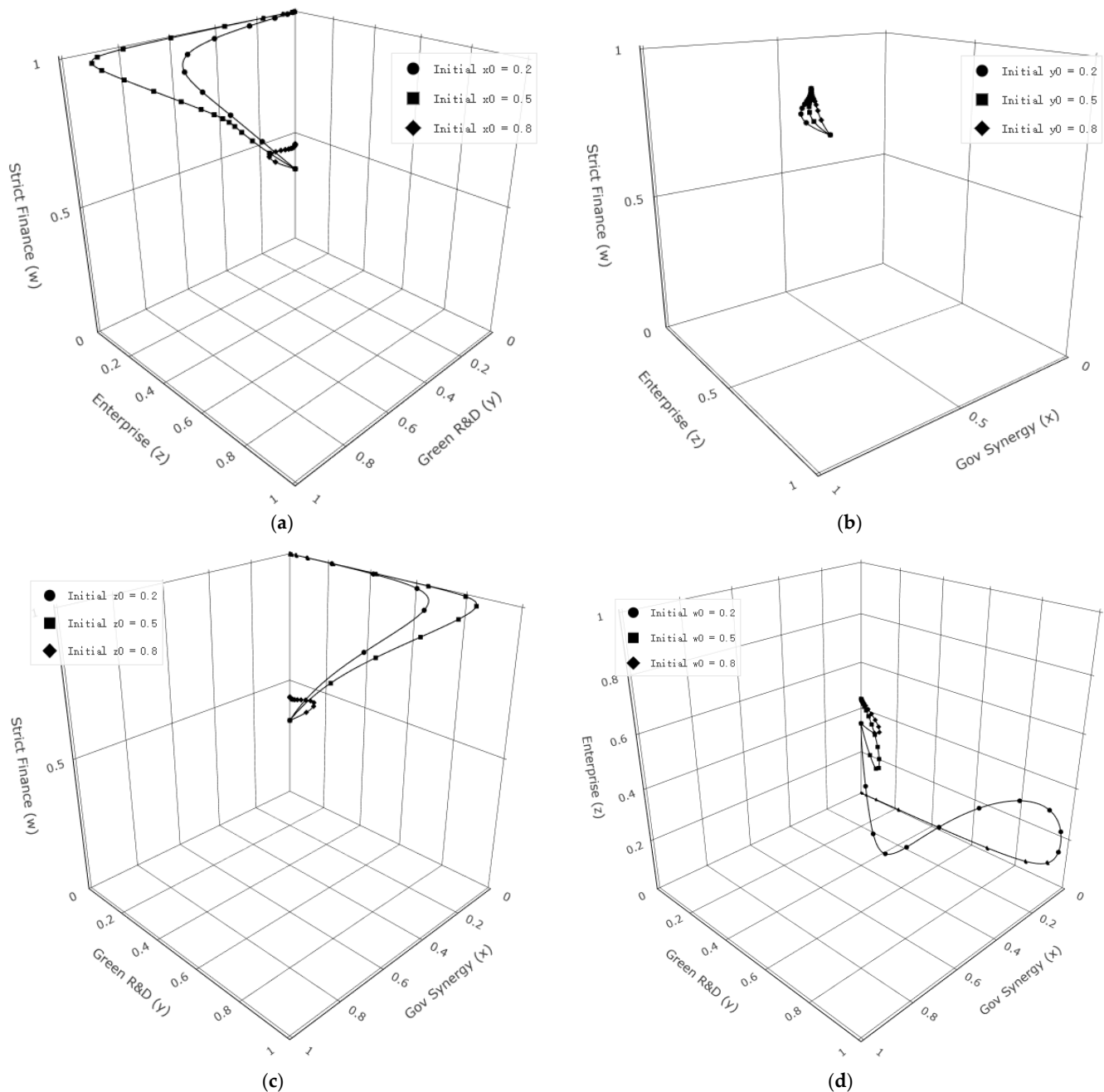


Figure 1. Effects of initial strategy probabilities: (a) impact of government; (b) impact of universities; (c) impact of enterprise; (d) impact of green financial institution.

4.2.2. Effect of Initial University Green R&D Probability

Figure 1b presents the effect of the initial probability of universities strengthening green R&D (y_0). The results show that a higher initial probability of university green R&D accelerates the evolution of the other actors toward cooperative strategies. This indicates that universities' initial willingness to engage in green R&D plays an important role in promoting technology supply and commercialization within the green collaborative innovation system. Stronger university participation improves enterprises' access to green technologies, enhances the expected benefits of technology application, and strengthens the incentives of regional governments and green financial institutions to maintain active support. Consequently, a higher initial probability of university green R&D facilitates the formation of a stable collaborative innovation system.

4.2.3. Effect of Initial Enterprise Transformation Probability

Figure 1c presents the impact of initial enterprise transformation probability (z_0) system evolution. The results indicate that a higher initial enterprise transformation willingness promotes faster convergence toward the cooperative equilibrium. As enterprises are the main actors responsible for implementing green technologies, their transformation willingness directly affects technology commercialization, government returns, and financial institutions' risk expectations. When the initial probability of enterprise transformation is low, other actors have weaker incentives to maintain active strategies because the expected benefits of collaboration are reduced.

4.2.4. Effect of Initial Green Financial Institution Support Probability

Figure 1d investigates the impact of the initial probability of green financial institutions adopting active support strategies (w_0). The results show that stronger initial participation by green financial institutions promotes enterprise transformation and accelerates the evolution of the entire system. This occurs because financial institutions influence enterprise decisions through credit screening, financing conditions, and risk constraints. A higher initial willingness to provide green financial support strengthens market-based incentives and reduces opportunistic behavior, thereby improving the stability of the green collaborative innovation system.

4.3. Sensitivity Analysis of Key Parameters

To further examine the robustness of the evolutionary results, sensitivity analyses were conducted by varying key parameters while keeping other parameters at their baseline values reported in Table 3. The selected parameters correspond to the main mechanisms identified in Section 3, including green development benefits, reputation losses, technology commercialization returns, fiscal support, enterprise subsidies, financial constraints, financial incentives, and bad debt risks.

4.3.1. Effects of Government Behavior on Evolutionary Paths

Figure 2 examines the effect of the macro-level green dividend T_g on enterprise evolutionary trajectories under different initial government collaboration conditions. In this simulation, T_g is assigned three values (25, 45, and 65), while other parameters remain unchanged at their baseline values. The three subplots represent different initial probabilities of regional government collaboration. Specifically, Figures 2a, 2b, and 2c correspond to $x_0 = 0.2, 0.5$, and 0.8 , respectively, while the initial probabilities of universities, enterprises, and green financial institutions remain unchanged.

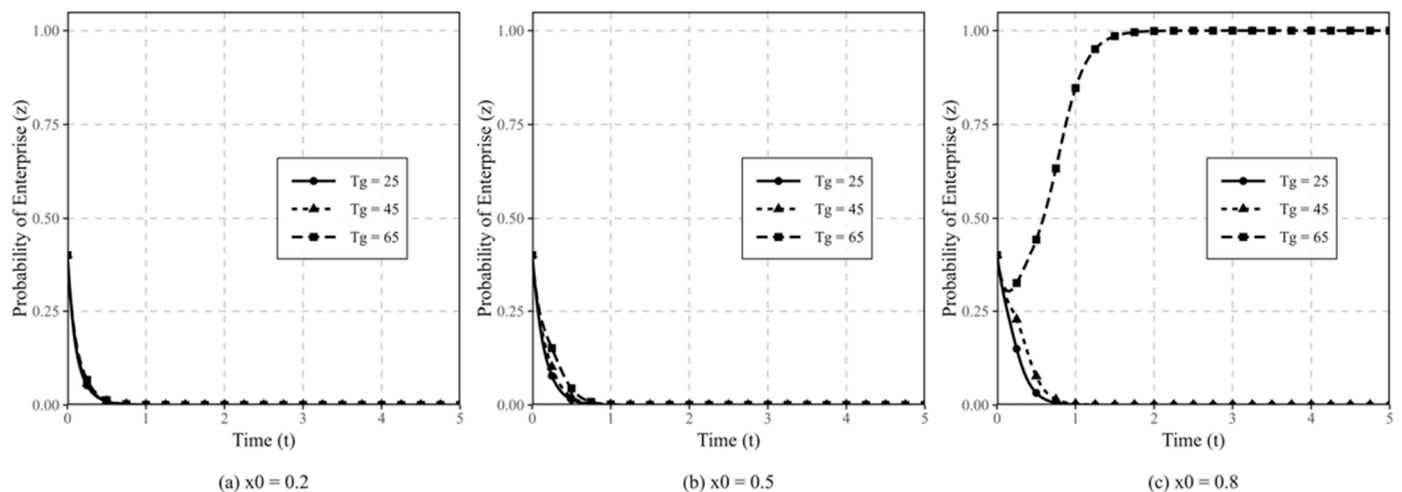


Figure 2. Effect of macro-level green dividends on evolutionary outcomes.

The results show that the effect of T_g depends on the initial willingness of regional governments to promote green collaboration. When x_0 is relatively low, increasing T_g has a limited effect because weak initial government commitment reduces the expected benefits of collaboration. However, when x_0 increases, a higher T_g significantly accelerates enterprise evolution toward deep green transformation. This finding is consistent with Proposition 1, indicating that increasing the economic returns generated by green collaboration can strengthen government commitment and promote the formation of a stable green collaborative innovation system.

Figure 3 examines the effect of government inaction loss M_g on enterprise evolutionary trajectories under different initial government collaboration conditions. In this simulation, M_g is assigned three values (5, 10, and 15), while other parameters remain unchanged at their baseline values. The three subplots represent different initial probabilities of regional government collaboration. Specifically, Figures 3a, 3b, and 3c correspond to $x_0 = 0.2$, 0.5, and 0.8, respectively, while the initial probabilities of universities, enterprises, and green financial institutions remain unchanged. The results show that the effect of M_g on enterprise green transformation varies with the initial willingness of regional governments to promote collaboration. When x_0 is relatively low, increasing M_g has a limited impact on enterprise evolution because insufficient government participation weakens the transmission of external governance pressure. As x_0 increases, the influence of M_g becomes more evident, and higher reputation and performance-assessment losses associated with government inaction accelerate enterprise evolution toward deep green transformation.

This result indicates that external governance pressure can complement economic incentives by increasing the cost of maintaining traditional development strategies. In particular, when regional governments have stronger initial willingness to participate in green collaboration, reputation and performance constraints become more effective in promoting green transformation. The finding is consistent with the theoretical analysis, suggesting that increasing the institutional costs of insufficient green governance can strengthen regional governments' commitment to collaborative innovation and facilitate the evolution of the entire system toward a greener development pathway.

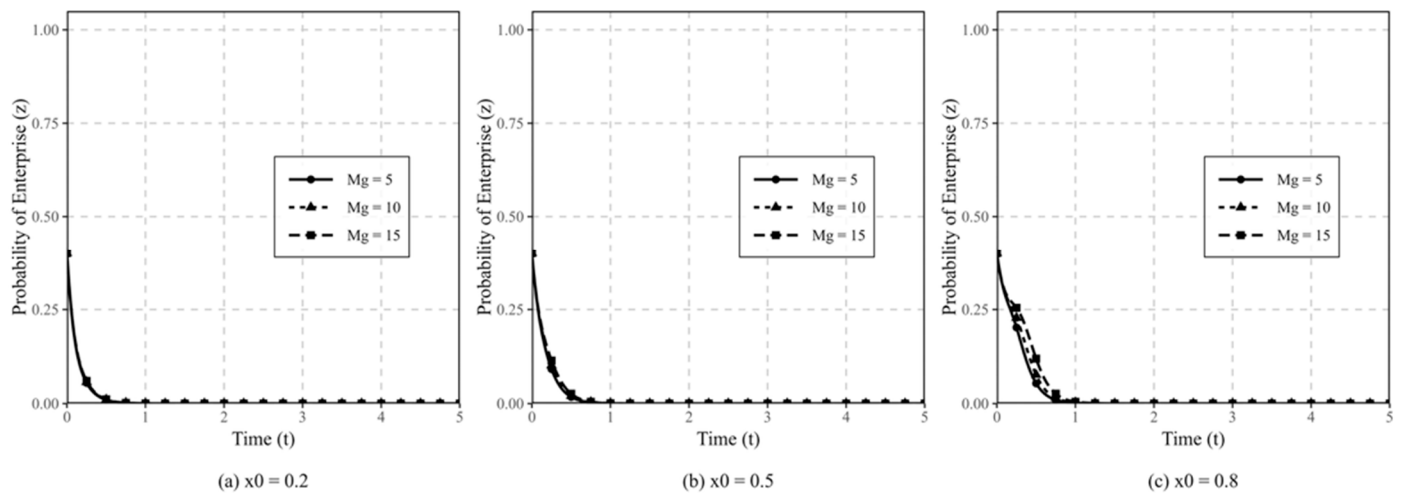


Figure 3. Effect of government inaction loss on evolutionary outcomes.

4.3.2. Effects of University Behavior on Evolutionary Paths

Figure 4 examines the effect of technology commercialization return W_u on enterprise evolutionary trajectories under different initial university green R&D conditions.

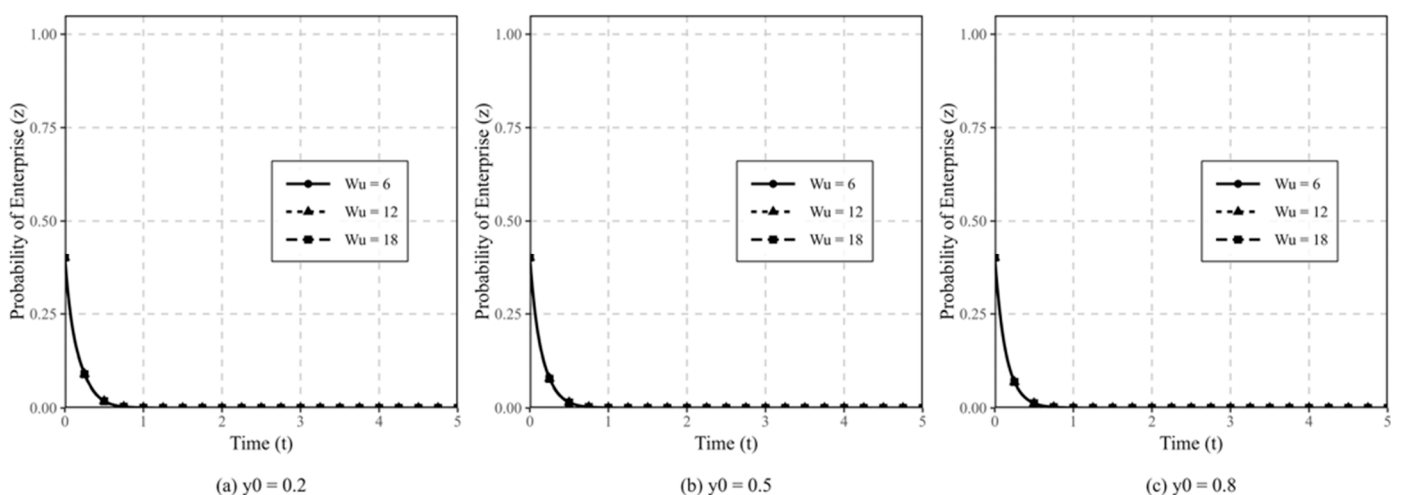


Figure 4. Effect of enterprise technology purchase payments on evolutionary outcomes.

In this simulation, W_u is assigned three values (6, 12, and 18), while other parameters remain unchanged at their baseline values. The three subplots represent different initial probabilities of university green R&D. Specifically, Figures 4a, 4b, and 4c correspond to $y_0 = 0.2$, 0.5, and 0.8, respectively, while the initial probabilities of regional governments, enterprises, and green financial institutions remain unchanged. The results show that the effect of technology commercialization returns on enterprise deep green transformation is closely related to the initial willingness of universities to engage in green R&D. When y_0 is relatively low, increasing W_u has a limited effect because insufficient university participation weakens the technology supply and commercialization process. As the initial probability of university green R&D increases, higher technology commercialization returns more effectively promote enterprise transformation.

This occurs because technology commercialization returns provide universities with stronger incentives to develop and transfer green technologies. When enterprises can obtain greater economic benefits from adopting green technologies, the expected returns of deep green transformation increase, thereby accelerating the evolution toward green

transformation. The result supports Proposition 2, indicating that improving technology commercialization mechanisms and strengthening university–industry linkages are important for enhancing the effectiveness of green collaborative innovation.

Figure 5 investigates the effect of government research funding T_s on the evolutionary trajectory of regional government collaboration under different initial university green R&D conditions. In this simulation, T_s is assigned three values (5, 10, and 15), while other parameters remain unchanged at their baseline values.

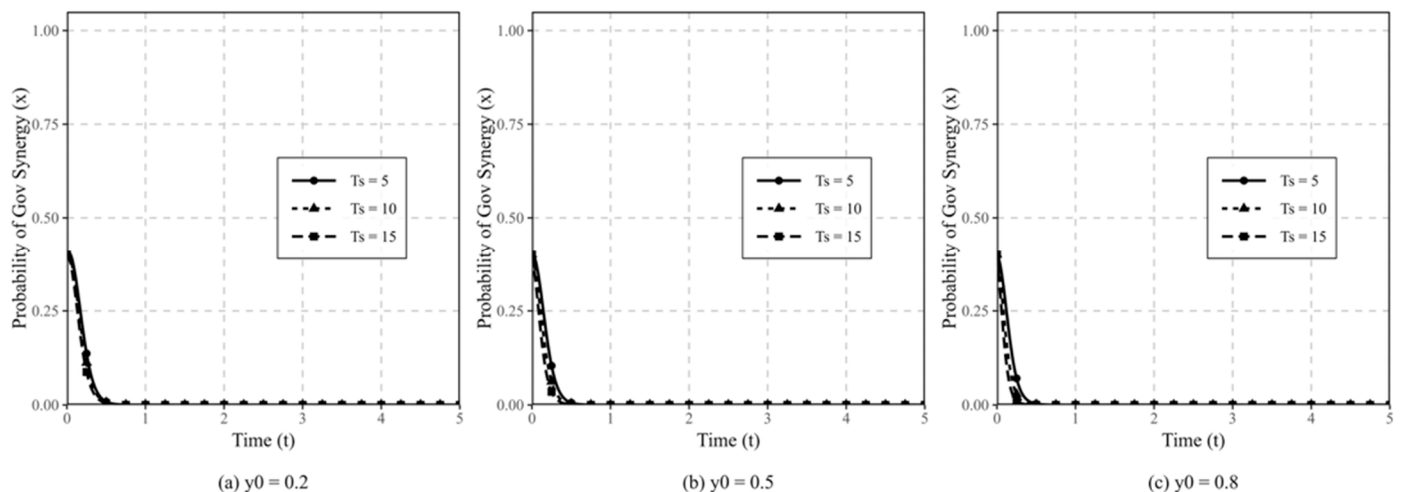


Figure 5. Effect of government research funding on evolutionary outcomes.

The three subplots represent different initial probabilities of university green R&D. Specifically, Figures 5a, 5b, and 5c correspond to $y_0 = 0.2$, 0.5, and 0.8, respectively, while the initial probabilities of regional governments, enterprises, and green financial institutions remain unchanged. The results indicate that the influence of government research funding depends on the initial willingness of universities to conduct green R&D. When y_0 is low, increasing T_s has a relatively limited effect because additional research funding cannot be efficiently transformed into technological outputs. When universities already demonstrate stronger green R&D willingness, excessive research funding may increase the financial burden on regional governments and weaken their willingness to maintain collaboration.

This result suggests that government research funding should be coordinated with universities' innovation capacity and regional fiscal conditions. Appropriate research support can enhance technology development, whereas excessive funding requirements may reduce the sustainability of government-led collaboration. The finding is consistent with the theoretical analysis, indicating that government support should focus not only on increasing research investment, but also on improving the efficiency of knowledge creation and technology commercialization.

4.3.3. Effects of Enterprise-Related Policies on Evolutionary Paths

Figure 6 examines the effect of enterprise subsidy S_e on the evolutionary trajectory of regional government collaboration under different initial enterprise transformation conditions. In this simulation, S_e is assigned three values (5, 15, and 25), while other parameters remain unchanged at their baseline values.

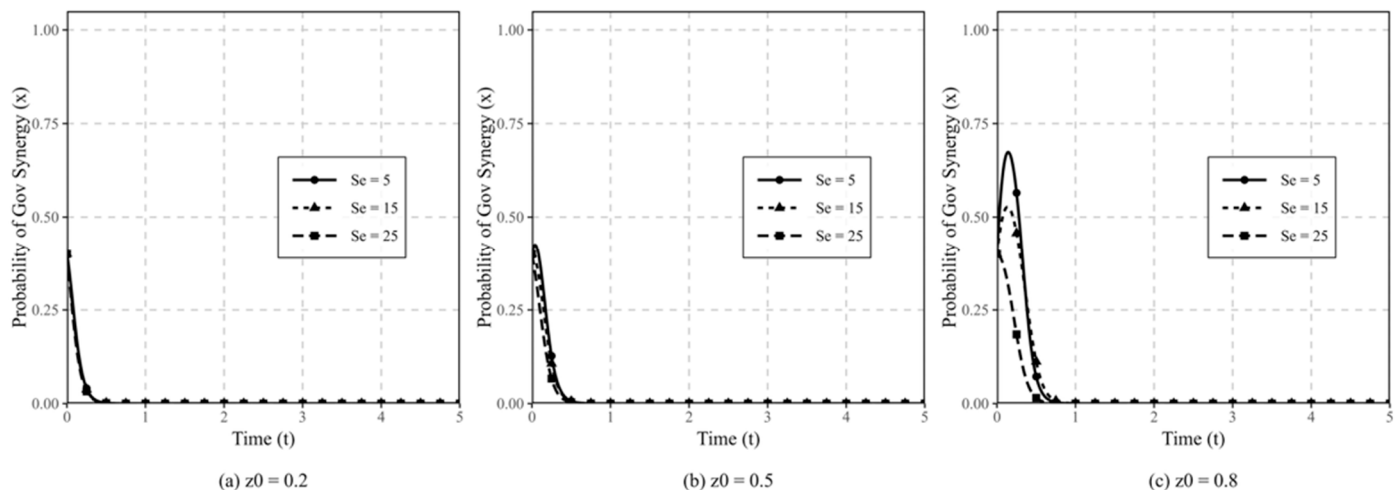


Figure 6. Effect of government subsidies to enterprises on evolutionary outcomes.

The three subplots represent different initial probabilities of enterprise deep green transformation. Specifically, Figures 6a, 6b, and 6c correspond to $z_0 = 0.2$, 0.5, and 0.8, respectively, while the initial probabilities of regional governments, universities, and green financial institutions remain unchanged. The results show that the effect of enterprise subsidies strongly depends on the initial willingness of enterprises to undertake green transformation. When z_0 is relatively low, increasing S_e has a limited effect on promoting government collaboration because insufficient enterprise transformation willingness reduces the expected returns generated by fiscal support. In contrast, when enterprises have stronger initial transformation willingness, higher subsidies more effectively promote the evolution of regional governments toward green collaboration.

This occurs because government subsidies reduce the effective transformation burden faced by enterprises and improve the expected returns of green transformation. However, subsidies alone cannot guarantee long-term collaboration when enterprises lack sufficient willingness to transform. The result is consistent with Proposition 3, indicating that fiscal incentives are effective only when they are combined with enterprise transformation capacity and broader collaborative mechanisms. Therefore, subsidy policies should focus on improving transformation performance rather than providing unconditional financial support.

Figure 7 investigates the effect of financial constraint F_e on the evolutionary trajectory of green financial institution support under different initial enterprise transformation conditions. In this simulation, F_e is assigned three values (5, 15, and 25), while other parameters remain unchanged at their baseline values.

The three subplots represent different initial probabilities of enterprise deep green transformation. Specifically, Figures 7a, 7b, and 7c correspond to $z_0 = 0.2$, 0.5, and 0.8, respectively, while the initial probabilities of regional governments, universities, and green financial institutions remain unchanged. The results demonstrate that stronger financial constraints accelerate the evolution of green financial institutions toward active support strategies. When F_e increases, the opportunity cost of enterprise non-compliance becomes higher, which strengthens the role of financial institutions as market-based regulators. The effect of F_e is more evident under lower initial enterprise transformation willingness. When z_0 is relatively low, stronger financial constraints provide additional incentives for financial institutions to conduct strict screening and encourage enterprises to improve their green performance. When enterprises already have high transformation willingness, the marginal effect of financial constraints becomes weaker because enterprises are already moving toward green transformation.

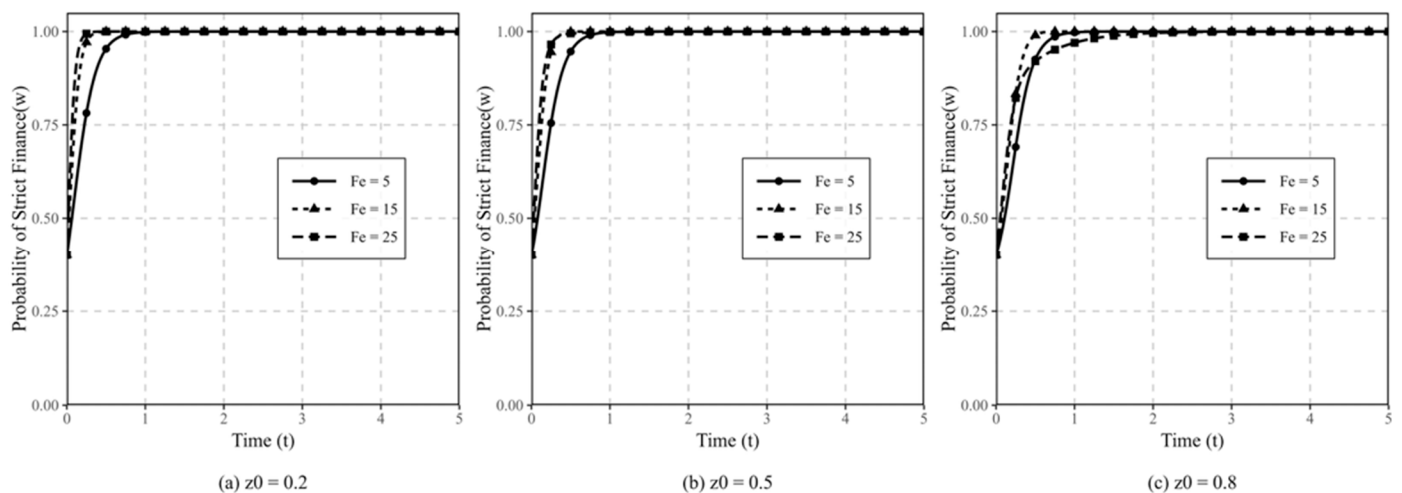


Figure 7. Effect of financial penalty interest on evolutionary outcomes.

This finding supports Proposition 3, demonstrating that financial constraints can complement government subsidies by increasing the cost of passive compliance. However, financial discipline should be balanced with supportive green finance mechanisms to avoid excessive restrictions on enterprise innovation activities.

4.3.4. Effects of Green Financial Institution Behavior on Evolutionary Paths

Figure 8 examines the effect of government incentives for green financial institutions S_f on the evolutionary trajectory of regional government collaboration under different initial financial institution support conditions. In this simulation, S_f is assigned three values (4, 8, and 12), while other parameters remain unchanged at their baseline values.

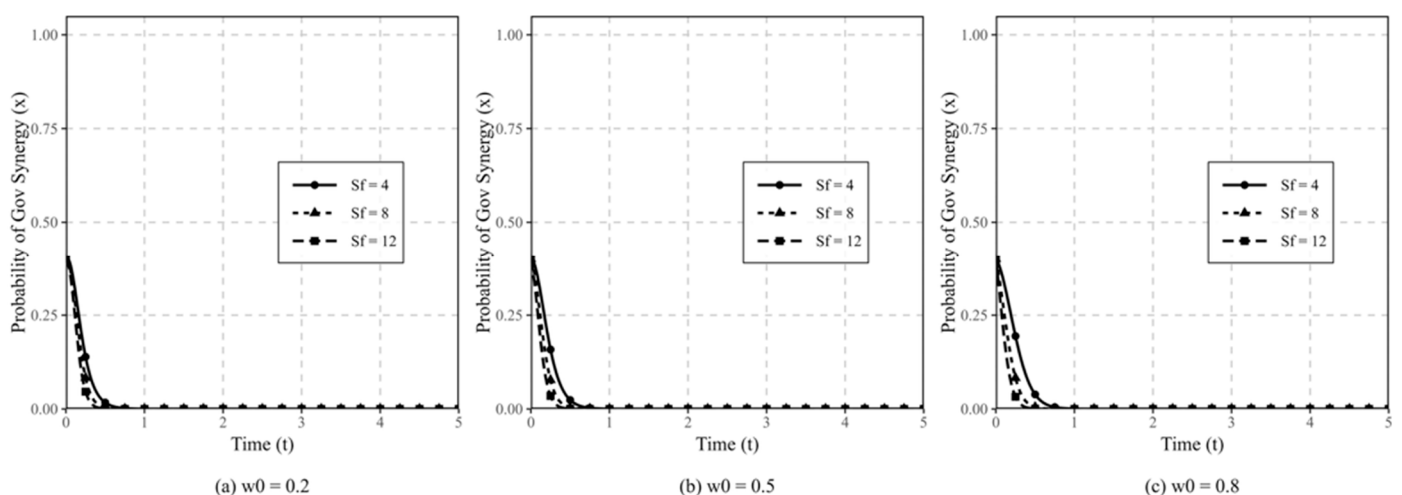


Figure 8. Effect of rewards to green financial institutions on evolutionary outcomes.

The three subplots represent different initial probabilities of green financial institutions adopting active support strategies. Specifically, Figures 8a, 8b, and 8c correspond to $w_0 = 0.2$, 0.5 , and 0.8 , respectively, while the initial probabilities of regional governments, universities, and enterprises remain unchanged. The results show that the influence of S_f depends on the initial participation willingness of green financial institutions. When w_0 is relatively low, increasing S_f has a limited effect on government collaboration because financial institutions initially lack sufficient willingness to participate in green innovation

governance. As w_0 increases, the effect of financial incentives becomes more evident by strengthening the role of green financial institutions in supporting collaborative innovation.

This occurs because S_f reduces the additional cost faced by financial institutions when implementing active green support strategies, including environmental assessment, credit screening, and risk monitoring. However, excessive reliance on government incentives may increase fiscal pressure and weaken the market-oriented nature of green finance. The result is consistent with Proposition 4, indicating that appropriate financial institution incentives can enhance green finance participation and improve the stability of the collaborative innovation system.

Figure 9 investigates the effect of bad debt risk N_f on enterprise evolutionary trajectories under different initial financial institution support conditions. In this simulation, N_f is assigned three values (4, 8, and 12), while other parameters remain unchanged at their baseline values.

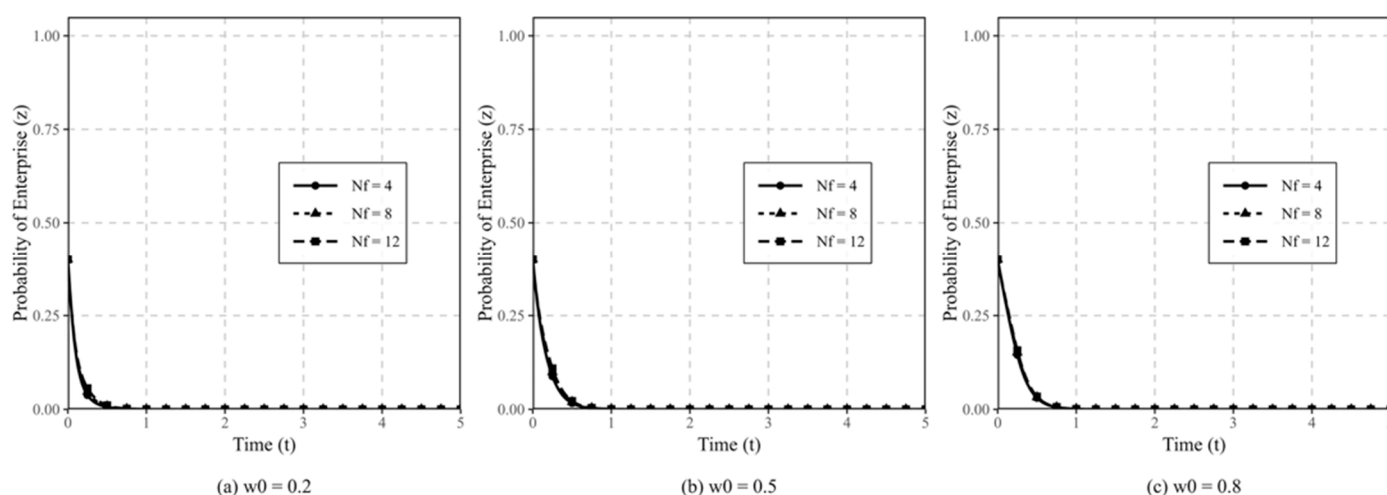


Figure 9. Effect of bad debt risk on evolutionary outcomes.

The three subplots represent different initial probabilities of green financial institutions adopting active support strategies. Specifically, Figures 9a, 9b, and 9c correspond to $w_0 = 0.2$, 0.5, and 0.8, respectively, while the initial probabilities of regional governments, universities, and enterprises remain unchanged. The results indicate that higher bad debt risk strengthens the tendency of enterprises to adopt deep green transformation. When N_f increases, green financial institutions face greater potential losses from providing conventional credit to enterprises with insufficient green performance, which encourages stricter screening and stronger financing constraints. The effect of N_f is more significant under lower initial financial institution participation. When w_0 is relatively low, increasing bad debt risk provides an additional incentive for financial institutions to shift toward active green support strategies. When financial institutions already have strong initial willingness to participate, the marginal effect of N_f becomes weaker.

This finding supports Proposition 4, demonstrating that financial risk perception can serve as a market-based mechanism that promotes green transformation. Therefore, improving green credit risk identification and early-warning mechanisms can strengthen the external pressure for enterprise green upgrading.

4.4. Joint Parameter Analysis and Robustness Analysis

4.4.1. Joint Effects of Government Subsidy and Financial Constraint

To further examine the interaction between fiscal incentives and market-based financial constraints, a joint parameter analysis of enterprise subsidy S_e and financial constraint

F_e was conducted. Unlike the previous sensitivity analyses that examined individual parameter changes separately, this simulation investigates how the combination of government support and financial discipline jointly influences enterprise deep green transformation.

Figure 10 presents the evolutionary trajectories of enterprise deep green transformation under different combinations of S_e and F_e . The three subplots represent different levels of enterprise subsidy, with $S_e = 5, 15$, and 25 , respectively. Within each subplot, three evolutionary trajectories correspond to different levels of financial constraint ($F_e = 5, 15$, and 25).

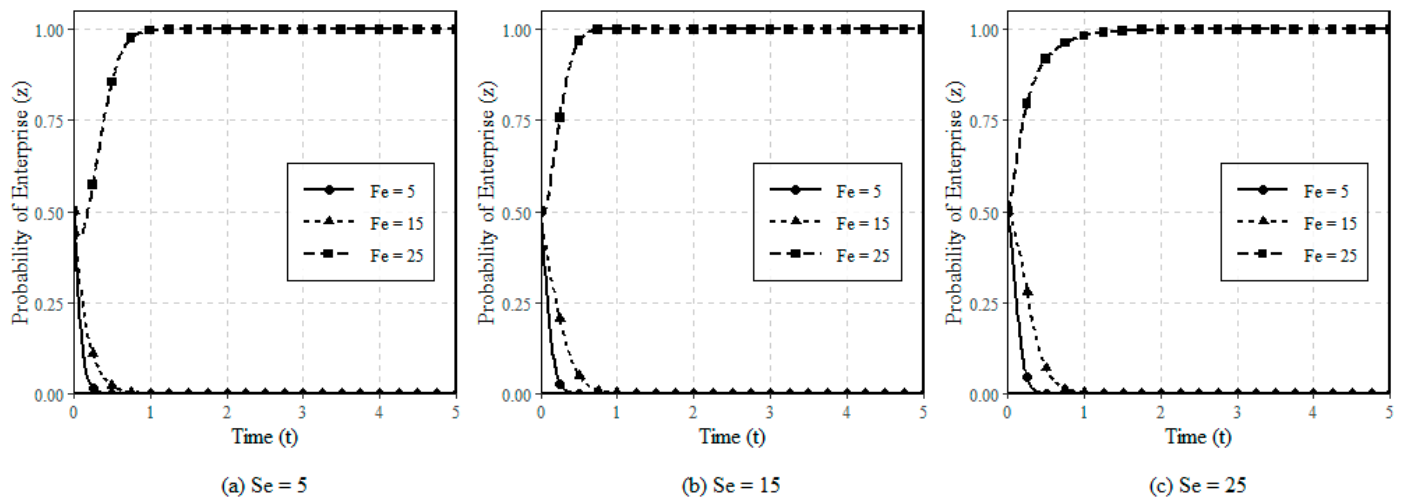


Figure 10. Joint effects of enterprise subsidy and financial constraint on enterprise deep green transformation.

The results demonstrate that the combined effect of government subsidies and financial constraints plays a decisive role in promoting enterprise deep green transformation. When both S_e and F_e are relatively low, enterprises tend to remain in the passive compliance transformation strategy because the expected benefits and external pressures are insufficient to offset the transformation cost. As shown in Figure 10a, low subsidy intensity requires stronger financial constraints to induce enterprises to move toward deep green transformation. With an increase in enterprise subsidies, the positive effect of financial constraints becomes more significant. In Figure 10b, higher levels of F_e accelerate the convergence of enterprises toward the deep green transformation strategy, indicating that financial constraints can effectively complement fiscal incentives by increasing the cost of non-compliance. When S_e reaches a higher level, as shown in Figure 10c, enterprises become more sensitive to financial mechanisms, and even moderate financial constraints can promote rapid transformation. This indicates that fiscal incentives reduce the transformation burden, while financial constraints provide continuous market pressure, and the combination of both mechanisms creates a stronger incentive structure than either instrument alone.

These results further validate Proposition 3, which suggests that enterprise transformation depends on whether the combined effects of government subsidies and financial constraints can overcome the transformation cost. Therefore, effective green transformation policies should avoid relying solely on government subsidies. Instead, governments should establish a coordinated mechanism combining fiscal incentives with green financial constraints, allowing market-based financial discipline to complement public policy support and improve the sustainability of green collaborative innovation.

4.4.2. Effect of Social Advocacy Probability

Figure 11 examines the effect of social advocacy probability k on the evolutionary trajectory of green financial institutions' active support strategy. In this simulation, k is assigned three values (0.2, 0.5, and 0.8), while other parameters remain unchanged at their baseline values.

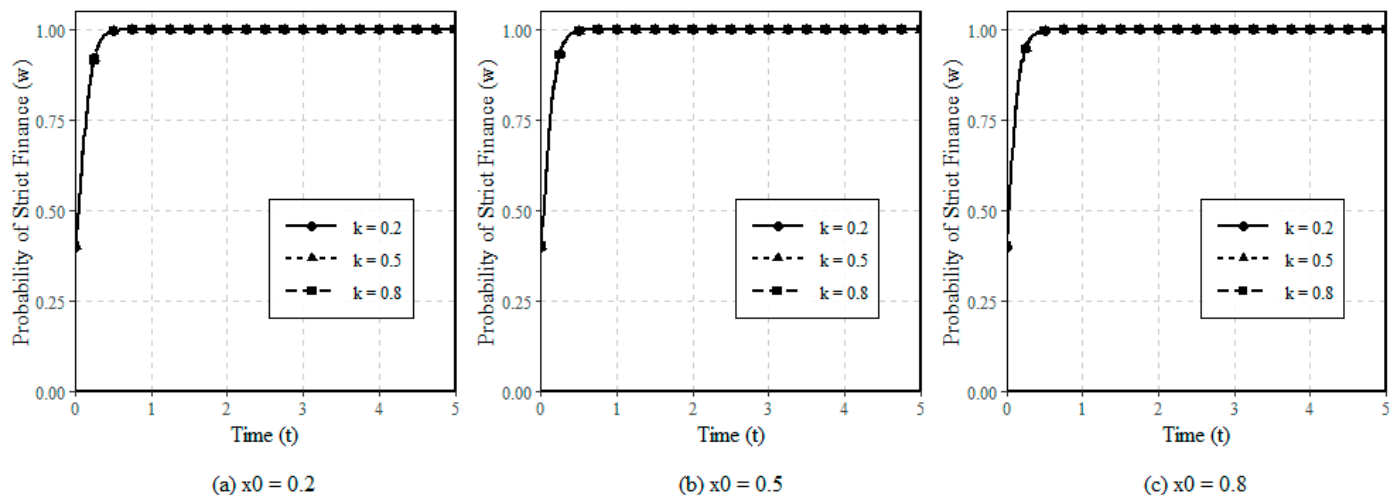


Figure 11. Effect of social advocacy probability.

The three subplots represent different initial probabilities of regional government collaboration. Specifically, Figures 11a, 11b, and 11c correspond to $x_0 = 0.2$, 0.5, and 0.8, respectively, while the initial probabilities of universities, enterprises, and green financial institutions remain unchanged. The results show that green financial institutions rapidly evolve toward the active green financial support strategy under all initial government collaboration conditions. Although changes in social advocacy probability k generate differences in the convergence trajectories, the overall evolutionary direction remains unchanged.

Specifically, a higher level of social advocacy slightly affects the convergence speed of green financial institutions toward active support. This result reflects the indirect transmission mechanism of informal institutional pressure. Since k does not directly enter the strategy selection equation of green financial institutions, its influence is transmitted through the reputation-related payoffs of regional governments and universities, thereby affecting the broader collaborative innovation environment.

The results indicate that social advocacy functions as a complementary governance mechanism rather than a substitute for formal regulation. Stronger social supervision can increase external pressure on reputation-sensitive actors and improve the effectiveness of informal governance. However, maintaining government coordination and appropriate financial incentives remains essential for sustaining long-term green financial support.

4.4.3. Robustness Analysis Under Boundary Conditions and Institutional Variations

To examine whether the evolutionary results remain robust under different parameter settings, additional simulations were conducted under boundary conditions and institutional variations.

Figure 12 presents three robustness tests. Figure 12a examines different policy intensity scenarios by jointly changing enterprise subsidies S_e and financial constraints F_e . Figure 12b evaluates the robustness of the model under different financial risk conditions by varying bad debt risk N_f and financial constraint intensity F_e . Figure 12c investigates the influence of social advocacy probability k as an external institutional factor. In Figure 12a, weak,

moderate, and strong policy intervention scenarios are constructed with $(S_e, F_e) = (5, 5)$, $(15, 15)$, and $(25, 25)$, respectively. The results show that stronger policy intervention accelerates enterprise deep green transformation, confirming that the combined effects of fiscal incentives and financial constraints determine whether enterprises can overcome the transformation costs. Figure 12b considers different financial risk environments. The results indicate that stronger financial constraints and higher bad debt risks accelerate the evolution of green financial institutions toward active support strategies. This finding confirms that financial discipline can complement government incentives by increasing the cost of passive compliance. Figure 12c examines the robustness of social advocacy effects. The results show that variations in k influence government collaboration trajectories but do not change the final evolutionary direction. This supports the assumption that social advocacy acts as an external institutional factor that modifies reputation-related payoffs rather than directly determining strategic choices.

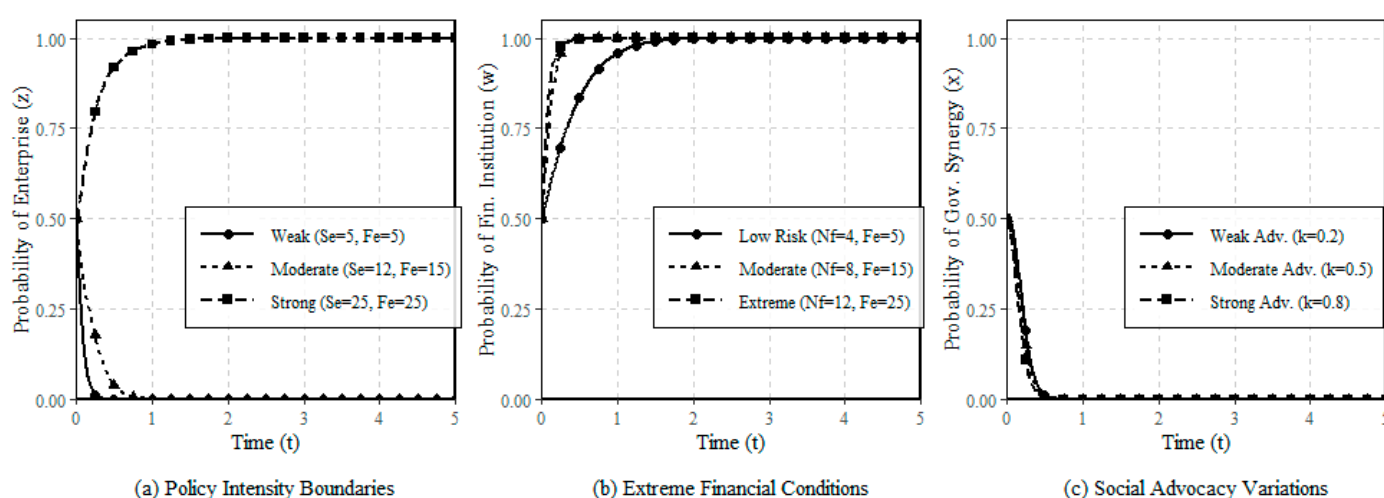


Figure 12. Robustness analysis.

Overall, the robustness tests demonstrate that the main evolutionary mechanisms remain stable under different policy intensities, financial conditions, and institutional environments.

4.4.4. Practical Applicability and Model Consistency

Although the proposed model was developed from a theoretical evolutionary perspective, the evolutionary mechanisms identified in this study are consistent with practical green innovation governance processes. China's Green Finance Reform and Innovation Pilot Zones provide a representative context where governments, financial institutions, and enterprises jointly promote green transformation through policy incentives, financial mechanisms, and environmental risk management.

The simulation results indicate that green collaborative innovation depends on the interaction among fiscal incentives, enterprise transformation costs, technology commercialization returns, and financial governance mechanisms. These mechanisms correspond to practical governance processes. Government subsidies and policy support reduce the initial barriers faced by enterprises during green transformation, while technology commercialization incentives encourage universities to transfer green technologies into industrial applications. Meanwhile, green financial institutions influence enterprise behavior through environmental risk assessment, differentiated credit allocation, and financing constraints.

Therefore, the proposed evolutionary framework provides a theoretical explanation for the dynamic coordination among governments, universities, enterprises, and financial institutions. Although this study does not directly calibrate model parameters using panel

data or firm-level observations, the identified evolutionary mechanisms are consistent with observed green finance practices and provide theoretical insights for understanding regional green innovation governance.

5. Conclusions

5.1. Research Findings

This study developed a four-player evolutionary game model involving regional governments, universities, local enterprises, and green financial institutions to investigate the evolutionary mechanisms of green collaborative innovation. The main findings are summarized as follows.

First, the evolution of green collaborative innovation is determined by the strategic interactions among multiple stakeholders rather than by the behavior of individual actors. The results show that governments, universities, enterprises, and financial institutions continuously adjust their strategies according to their expected payoffs, and the evolutionary outcomes depend on whether the benefits of collaboration can compensate for the associated costs and risks. The stability analysis further indicates that the system may evolve toward either a low-collaboration state or a coordinated green innovation state under different parameter conditions.

Second, the study identifies the key mechanisms influencing the transition toward green collaborative innovation. Enterprise deep green transformation serves as the core link connecting government policies, university innovation, and financial support. The combined effects of government subsidies and financial constraints determine whether enterprises can overcome transformation costs. Meanwhile, technology commercialization returns and research support influence universities' incentives for green R&D, while policy incentives and risk considerations shape the participation of green financial institutions. These findings demonstrate that green collaborative innovation depends on the alignment of economic incentives among different actors.

Third, the results highlight the importance of coordinated institutional arrangements in promoting green transformation. Formal mechanisms, including fiscal subsidies, financial regulation, and policy incentives, provide direct support for collaborative innovation, whereas informal mechanisms such as social advocacy influence the system through reputation-related effects. The findings suggest that effective green collaborative innovation requires the integration of government guidance, market-based financial mechanisms, technology commercialization channels, and institutional supervision rather than reliance on a single policy instrument.

5.2. Theoretical Contributions

This study contributes to the literature on green collaborative innovation and evolutionary game theory in three aspects.

First, this study extends existing research on green collaborative innovation by developing a four-player evolutionary framework that incorporates regional governments, universities, local enterprises, and green financial institutions. Previous studies have mainly focused on government–enterprise interactions or university–industry–government collaboration, while the role of financial institutions has often been treated as an external environmental factor. By introducing green financial institutions as an independent strategic actor, this study provides a more comprehensive understanding of how financial mechanisms participate in and influence the evolution of green innovation systems.

Second, this study advances the understanding of the transition mechanisms underlying green collaborative innovation by revealing the joint effects of fiscal incentives, financial constraints, and technology commercialization. Existing studies have generally examined

these factors separately, whereas this study demonstrates that green transformation is the result of interactions among multiple incentive mechanisms. In particular, the model identifies how government subsidies, financial constraints, technology commercialization returns, and research support jointly influence actors' strategic choices and determine whether the system can overcome transformation barriers.

Third, this study enriches the theoretical understanding of institutional governance in green innovation systems by integrating formal and informal institutional mechanisms into the evolutionary framework. Formal mechanisms, including government regulation, fiscal incentives, and financial supervision, directly influence strategic decisions, while informal mechanisms such as social advocacy affect reputation-related payoffs and indirectly shape evolutionary outcomes. By incorporating social advocacy probability k , this study provides insights into how informal institutional pressure complements formal governance mechanisms in promoting sustainable innovation.

5.3. Policy Implications

The findings of this study provide several mechanism-oriented policy implications for promoting green collaborative innovation. Rather than relying on broad policy interventions, policymakers should focus on improving incentive compatibility among different actors and reducing the barriers that hinder green transformation.

First, policymakers should establish a coordinated incentive mechanism that combines fiscal support with market-based financial regulation. The results show that enterprise green transformation is influenced by both government incentives and financial mechanisms. Therefore, governments should avoid relying solely on direct subsidies and instead develop differentiated support policies based on enterprises' transformation capabilities and environmental performance. Fiscal incentives can be targeted toward enterprises with strong innovation potential, while green financial mechanisms can provide continuous market-based incentives and constraints. Such coordination can reduce enterprises' dependence on subsidies and improve the efficiency of green transformation policies.

Second, policymakers should strengthen technology commercialization mechanisms to enhance the contribution of universities to green innovation. The findings indicate that technological development alone is insufficient to promote green transformation unless innovation achievements can be effectively transferred into industrial applications. Therefore, governments should improve industry–university–research collaboration platforms, strengthen intellectual property protection, and develop efficient technology transfer mechanisms. Enhancing the commercialization value of green technologies can increase universities' incentives for green R&D and support enterprises in overcoming technological barriers during transformation.

Third, policymakers should develop a multi-level governance framework that integrates government coordination, green finance, and social supervision. The results highlight that green financial institutions play an important role not only in resource allocation, but also in environmental risk governance. Governments should encourage financial institutions to strengthen green project evaluation, environmental risk assessment, and differentiated financial services. Meanwhile, social advocacy and public supervision should be utilized as complementary governance mechanisms to enhance environmental accountability and information transparency. However, informal institutional pressure should not replace formal regulatory coordination, and government leadership remains essential for maintaining long-term collaboration among different actors.

Overall, effective green collaborative innovation requires the integration of fiscal incentives, financial mechanisms, technology commercialization, and institutional governance. A coordinated policy framework can align the interests of governments, universities, en-

terprises, and financial institutions, thereby increasing the likelihood of achieving a stable green innovation ecosystem.

5.4. Limitations and Future Research

Despite the contributions of this study, several limitations remain and provide directions for future research.

One limitation is that this study developed a theoretical evolutionary game model and relied on numerical simulations to investigate the evolutionary mechanisms of green collaborative innovation. Although the parameter settings were established based on theoretical relationships and practical considerations, the model does not directly incorporate empirical calibration. Future research could combine the proposed framework with regional or firm-level panel data to estimate key parameters and further validate the evolutionary mechanisms identified in this study.

Another limitation is that the model simplifies the green collaborative innovation system by assuming relatively homogeneous actors and focusing on interactions among four major stakeholders. In practice, enterprises, universities, governments, and financial institutions may differ in their technological capabilities, resource conditions, and institutional environments. Future studies could introduce greater heterogeneity among actors, incorporate additional stakeholders, and consider dynamic policy adjustments to further improve the applicability of the model.

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