

Article

Promoting Sustainable Co-Production of Community Safety in China: A Tripartite Evolutionary Game Analysis

Sheng Zhang , Linli Tao  and Chao Liu * 

School of Public Administration, Xiangtan University, Xiangtan 411100, China;
shengzhang@smail.xtu.edu.cn (S.Z.); linnetao@smail.xtu.edu.cn (L.T.)

* Correspondence: liuchao@xtu.edu.cn; Tel.: +86-18673233009

Abstract

Co-production plays an important role in improving community safety worldwide. However, in China's governance system, where governmental authority remains strong, enterprises and the public have traditionally been passive participants, creating multiple challenges for the development of co-production. To address these challenges, this study examines the behavioral patterns and strategic choices of grassroots governments, property service enterprises (PSEs), and community residents in co-producing community safety. A tripartite evolutionary game model is constructed as the analytical framework, and the "Property Deliberation Council" (PDC) practice in Changsha is used to calibrate the parameters and conduct simulation analysis. The study explores the interest interactions and stability mechanisms among the three actors in community safety co-production. The results show that, under the benchmark parameter settings, the system can evolve toward an ideal stable state characterized by guided cooperation from grassroots governments, active cooperation from PSEs, and active participation from community residents. Moderate government incentives can increase the participation benefits of enterprises and residents, whereas excessive incentives may increase the cost burden on governments. Information transparency and sanction intensity generate a synergistic constraint effect. Social capital can reduce cooperation costs, suppress opportunistic behavior, and promote the transition of co-production from external mobilization to endogenous stability. This study argues that community safety co-production in the Chinese context is neither simple administrative mobilization nor citizen-led co-production. Rather, it is a governance process jointly shaped by government guidance, the embedded role of PSEs, and resident participation. The findings provide theoretical explanations and policy implications for improving community safety governance platforms, strengthening information disclosure and accountability mechanisms, cultivating community social capital, and promoting sustainable community safety co-production.



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1. Introduction

Currently, complex and uncertain risks embedded in communities, together with various destabilizing factors, are increasingly intertwined and emerging. Community safety challenges, such as public security incidents, social conflicts and disputes, and fire hazards, frequently occur in local communities. These risks not only undermine residents' sense of security but also threaten the normal functioning and stability of grassroots social

governance systems [1–3]. In China, community safety governance has long been dominated by the government. Although this governance model demonstrates clear advantages in resource mobilization and rapid response, a governance approach relying solely on administrative forces faces inherent limitations in information acquisition, governance costs, and adaptive responsiveness, making it difficult to effectively address increasingly complex community safety challenges [4]. In recent years, relevant policy documents have continuously emphasized the participation of multiple actors in grassroots and community governance, calling for a governance pattern led by grassroots governments, coordinated by social forces, and widely supported by the public [5,6]. This indicates that community safety governance needs to move from unilateral governmental provision and administrative provision toward multi-actor participation and collaborative governance.

Against this background, co-production theory provides an important perspective for understanding and promoting the sustainable transformation of community safety governance. This theory holds that public services are not the result of unilateral governmental provision but are produced through the joint input of resources, knowledge, and actions by governments, service organizations, and citizens, thereby jointly creating public value [7–9]. Within the specific context of community safety governance in China, grassroots governments (In this study, “grassroots governments” refer to grassroots governance actors that directly undertake community-level public safety governance responsibilities in China’s urban governance system, including subdistrict offices, township governments, community committees, local police stations, and related grassroots governance organizations.) possess capacities for institutional provision, platform building, organizational mobilization, and accountability supervision. Compared with other community-based social organizations, property service enterprises (PSEs) serve as daily operational actors in community safety governance and undertake important functions, including security inspections, facility maintenance, access control management, fire safety management, and frontline risk response. Positioned at the interface between grassroots governments and community residents, their active engagement can provide an important complement to existing community safety governance arrangements. Community residents have advantages in daily risk perception, hazard reporting, public supervision, and emergency cooperation. Therefore, the sustainable governance of community safety is not simply a “safety service” provided unilaterally by the government but a co-production process in which grassroots governments, PSEs, and community residents jointly invest resources, share information, and coordinate their actions.

However, in China’s governance context, characterized by top-down governance and relatively weak traditions of active participation among market actors and the public, community safety co-production does not emerge spontaneously [10]. Grassroots governments may face high administrative costs, insufficient participation by social actors, and ambiguous boundaries of responsibility. As market-oriented service providers, PSEs need to invest additional human, financial, and time resources when actively cooperating with the government in governance. Community residents, as direct beneficiaries of community safety and everyday risk perceivers, may also adopt a passive attitude due to high participation costs, insufficient trust, or free-riding incentives. Therefore, it is necessary to examine how community safety co-production is initiated, maintained, and stabilized in China’s strongly government-led community governance context. Based on the above discussion, this study focuses on the following research questions:

RQ1. How do grassroots governments, PSEs, and community residents make strategic choices and interact under bounded rationality in community safety co-production?

RQ2. Under what conditions can the system stably evolve into a co-production state characterized by “guided cooperation by grassroots governments–active cooperation by PSEs–active participation by community residents”?

RQ3. How do government incentives, information transparency, sanction constraints, social capital, and opportunistic benefits affect the evolutionary direction of the system?

To address the above research questions, this study introduces an evolutionary game approach and constructs a tripartite evolutionary game model involving grassroots governments, PSEs, and community residents. The model is used to analyze the strategic choices and stability conditions of each actor under different scenarios. MATLAB R2025b is then employed to simulate the behavioral evolution of the three actors and the effects of key influencing factors. In addition, this study uses the “Property Deliberation Council” (PDC) practice in Changsha as a contextual case to calibrate parameters and interpret mechanisms, and further proposes policy recommendations to promote sustainable community safety co-production. This study provides valuable insights into the broader application of multi-actor co-production models in highly urbanized contexts.

The marginal contributions of this study are threefold. First, this study expands the actor structure of community safety co-production. Unlike existing studies that mainly focus on government–citizen or professional–citizen relationships, this study incorporates PSEs as market actors into the co-production framework and develops a tripartite framework involving grassroots governments, PSEs, and community residents. It further reveals how PSEs balance public governance responsibilities, operational costs, reputational gains, and opportunistic gains in the co-production process. Second, this study further examines the mechanism of government-guided co-production. The findings demonstrate that government-guided co-production does not replace non-government actors in public service provision; rather, it reshapes the payoff structures of PSEs and community residents through institutional platforms, incentives, sanctions, information transparency, and accountability mechanisms while preserving their strategic autonomy and substantive engagement. Third, this study reveals the dynamic evolutionary and stabilization mechanisms of collective co-production in community safety governance. Beyond identifying how government incentives, information transparency, sanctions, social capital, and opportunistic gains affect participation decisions, this study further demonstrates the moderating effects of appropriate incentives, the complementarity between transparency and sanctions, and the role of social capital in reducing cooperation costs and constraining opportunistic behaviors. These findings explain how multi-actor participation evolves from fragmented and unstable states toward a stable tripartite co-production equilibrium.

2. Literature Review

2.1. Community Safety Governance and the Transformation of Participating Actors: From Governmental Provision to Multi-Actor Collaboration

Community safety governance is an important component of urban grassroots governance and sustainable community development. Early studies on community safety and policing mainly adopted a crime-control perspective, using indicators such as crime reduction, decreases in public security incidents, disorder control, and reductions in fear of crime to evaluate the performance of public safety governance [11,12]. Subsequent studies have argued that community safety should also include broader dimensions, such as residents’ sense of safety, risk perception, public space order, neighborhood relations, community trust, and emergency response capacity [2,13]. Along with this expansion in the scope of governance, the actors involved in community safety governance have also shifted from single-governmental provision to multi-actor collaboration. In his early research on metropolitan policing, Ostrom pointed out that public safety performance does not depend

solely on police or governmental input but is closely related to residents' provision of information, supervision, preventive actions, and cooperation with public agencies [14]. Van Eijk et al. also noted that community safety requires residents to observe, report, patrol, and cooperate with professionals [15]. Guo and Li, in their study of collaborative governance regimes for community safety in China and South Korea, further showed that, when facing sudden and complex risks, community safety governance requires collaboration among governments, social organizations, residents, and other actors [4]. Thus, the actor structure of community safety governance has gradually shifted from a unilateral provision model dominated by governments or the police toward a collaborative governance model involving governments, professional organizations, market actors, community organizations, and residents.

However, existing studies on community safety governance have mainly focused on police–resident, government–resident, or professional–citizen relationships, with limited attention to market actors such as PSEs that are deeply embedded in the everyday functioning of residential communities. With the deepening of urbanization in China and the transition from the “work-unit system” to the “community system”, PSEs have evolved from simple building managers into important collaborative actors in grassroots social governance. They have dual attributes as market-oriented service providers and governance participants that undertake certain public functions [16,17]. In practice, PSEs have gradually expanded their roles beyond routine service provision to include community risk prevention and emergency response, benefiting from their close proximity to residents, access to community-level information, and rapid response capabilities [18]. As a result, they have increasingly become the “first line of defense” in community risk prevention and an important “frontline outpost” in emergency management [19]. However, as market actors operating through service contracts and relying on service fees, PSEs may simultaneously face the dual pressures of fulfilling government policy requirements and responding to residents' routine service demands [20]. Consequently, their decisions regarding the allocation of personnel, resources, and effort to community safety affairs involve a distinctive set of strategic trade-offs [21]. Accordingly, incorporating PSEs into the actor structure of community safety governance helps move beyond the traditional government–resident binary framework and more accurately reveal the tripartite interaction among grassroots governments, PSEs, and community residents.

2.2. Co-Production Theory and Community Safety Co-Production in the Chinese Context

Against the backdrop of the above transition toward multi-actor participation in community safety governance, co-production theory provides an important theoretical lens for understanding the joint participation of citizens and third-sector actors in public service provision. It has significant value for strengthening local democracy and civic awareness, promoting resource complementarity within governance networks, and aggregating value consensus among multiple actors. It is therefore conducive to the formation of collaborative community safety governance networks and to the effective use of social capital [22,23]. Early studies challenged the traditional assumption that public services are provided unilaterally by governments or professional organizations, emphasizing that service users, volunteers, private enterprises, government agencies at other levels, and community organizations can jointly invest resources and jointly influence public service outcomes [24,25]. The role of users and communities should not remain limited to “participation” or “expressing opinions”, but should extend to the design, management, delivery, and evaluation of public services [7]. As research has advanced, co-production studies have gradually shifted from a focus on “joint service provision” to “public value co-creation”, emphasizing the process by which citizens, organizations, and governments jointly create public value [9]. At

the same time, Brandsen et al.'s distinction among different types of co-production suggests the need to further examine "who participates, what they participate in, and under what institutional relationships they participate" [26]. Based on the participating units and the scope of beneficiaries, Nabatchi et al. distinguish among individual co-production, group co-production, and collective co-production [27]. Individual co-production occurs when a lay actor works directly with a state actor to create benefits primarily for the individual. Group co-production occurs when one or more state actors work directly with a group of lay actors who share common characteristics or interests to generate individual or collective benefits. Collective co-production occurs when one or more state actors work directly with multiple lay actors to create benefits for society as a whole. Today, co-production has become an important topic in public service research and has been widely applied in fields such as public administration, education, and healthcare [28–30].

Existing research has also identified the drivers of co-production from the perspectives of individual motivation, cost–benefit considerations, self-efficacy, institutional support, and social capital. Alford incorporated material rewards, sanctions, reputation, normative appeals, and intrinsic rewards into the motivational framework of co-production, arguing that actor participation is not driven solely by public spirit but is jointly shaped by cost–benefit considerations, social norms, and institutional incentives [25]. Voorberg et al. argued that monetary incentives are not always effective and that co-production depends more on the fit between incentive arrangements and participation contexts [9]. Lee and Na also found that value-based drivers, such as public service motivation and normative motivation, are associated with willingness to participate in co-production, whereas monetary or non-monetary rewards have limited effects [31]. Based on a large-scale survey across five countries, Parrado et al. found that government information provision and public consultation mechanisms are associated with the level of citizen co-production [32]. Pestoff argued that co-production depends not only on cost–benefit calculations, but also on changes in relationships and sustained interactions between public service personnel and citizens [33]. Jakobsen found, in a randomized field experiment, that government-provided information and behavioral suggestions can increase citizens' co-production behavior [22]. Wang and Zhang, through two scenario experiments, further found that goal framing and time framing can affect citizens' willingness to participate in co-production, with the combination of loss framing and present-oriented framing being most effective in promoting participation [34].

Although co-production theory emphasizes the joint creation of public value by multiple actors, the modes through which cooperation is initiated and institutionally organized vary across governance contexts. Citizen-led or community-led co-production is primarily driven by citizens or community organizations, which identify collective needs, initiate cooperation, and make substantive contributions throughout the public service process [35]. In governance systems characterized by strong governmental leadership and weak traditions of participation among market actors and the public, community safety co-production in the Chinese context exhibits features of institutional embeddedness and government guidance, which distinguish it from the aforementioned forms of co-production [36,37]. For example, in studies of urban policy pilots in China, Li et al. argue that co-production can be initiated and promoted by state or local governments, with governments playing an active role in resource input, platform construction, and process facilitation [38]. Ma et al.'s study of the political features of public service co-production also showed that political institutions and governmental behavior profoundly influence the organizational form and implementation mechanism of co-production [39]. However, this form of co-production differs from purely administrative mobilization. Administrative mobilization primarily relies on government directives to temporarily mobilize organizational and policy resources

and emphasizes achieving policy outcomes within a specified period [40]. In contrast, under government-guided co-production, market actors and citizens are not merely passive implementers of administrative mandates; rather, they actively invest resources, assume responsibilities, and contribute to public value creation based on their own assessments of costs and benefits under government guidance.

Overall, existing studies have provided an important foundation for understanding multi-actor participation, institutional arrangements of co-production, and the factors influencing co-production in community safety governance. However, three limitations remain. First, research on community safety governance and co-production has primarily focused on government–resident or professional–citizen relationships. Although the role of PSEs in community governance and emergency response has gradually received attention, limited analysis has examined how PSEs, as market actors, balance public governance responsibilities with their own business interests. Second, existing studies have demonstrated that co-production can be initiated and facilitated by national or local governments. However, insufficient attention has been paid to how governments reshape the cost–benefit structures of non-government actors through institutional platforms, incentives, sanctions, information transparency, and accountability mechanisms while maintaining their strategic autonomy and promoting substantive cooperation. Third, although previous research has identified various motivational and institutional factors influencing co-production, it has generally focused on individual factors or specific categories of participants. Limited attention has been given to how boundedly rational actors repeatedly adjust their strategies based on other actors’ choices and changes in relative payoffs, and how external institutional arrangements and internal social relations jointly shape the evolutionary trajectories and stability conditions of co-production.

3. Tripartite Evolutionary Game Model

Considering the above research gaps, evolutionary game theory, which is based on bounded rationality and dynamic evolution, provides a useful approach for understanding the interactions among stakeholders in community safety governance [41]. In recent years, evolutionary game theory has been widely applied to fields such as urban renewal [42], emergency management [43], and urban waste management [44]. However, its application in the field of community safety remains largely unexplored. Under China’s existing governance model, community safety affairs are increasingly initiated and promoted by the government. Market actors primarily interact with the government and the public as service providers, while community residents participate in governance through voluntary activities, safety patrols, hazard reporting, and deliberative consultation [45]. Therefore, this study applies the evolutionary game approach to analyze the interest roles and strategic choices of grassroots governments, PSEs, and community residents in the co-production of community safety.

To provide a contextual basis for identifying the participating actors, strategic choices, and interaction mechanisms, this study refers to the PDC practice in Changsha, Hunan Province. The “Property Deliberation Council” (PDC) is a community safety deliberation mechanism initiated and organized by local police stations and housing and urban–rural development departments. Within this mechanism, grassroots government actors, including local police stations, subdistrict offices, and community organizations, undertake responsibilities such as institutional provision, platform development, organizational coordination, and incentive and sanction implementation. PSEs are responsible for security patrols, facility maintenance, information reporting, routine inspections, and emergency response. Community members, including residents, building representatives, Party members, lawyers, and public security volunteers, participate in activities such as report-

ing safety risks, engaging in safety deliberations, supporting emergency response, and contributing to community co-governance. The PDC operates through mechanisms including joint consultation, coordinated prevention and response, regular training, information reporting, performance evaluation, and incentive arrangements, reflecting the interactive relationship among government guidance, enterprise cooperation, and resident participation.

The PDC practice provides a practical reference for the abstract model by supporting the identification of participating actors, the extraction of interaction mechanisms, the specification of strategic choices, and the calibration of simulation parameters and the interpretation of evolutionary mechanisms. Therefore, community safety co-production can be understood as a strategic interaction process among three types of actors: grassroots governments (including local police stations, housing and urban–rural development departments, subdistrict offices, and community committees), PSEs, and community residents (including community elites and community patrol volunteers). The responsibilities and interaction relationships among these actors are shown in Figure 1.

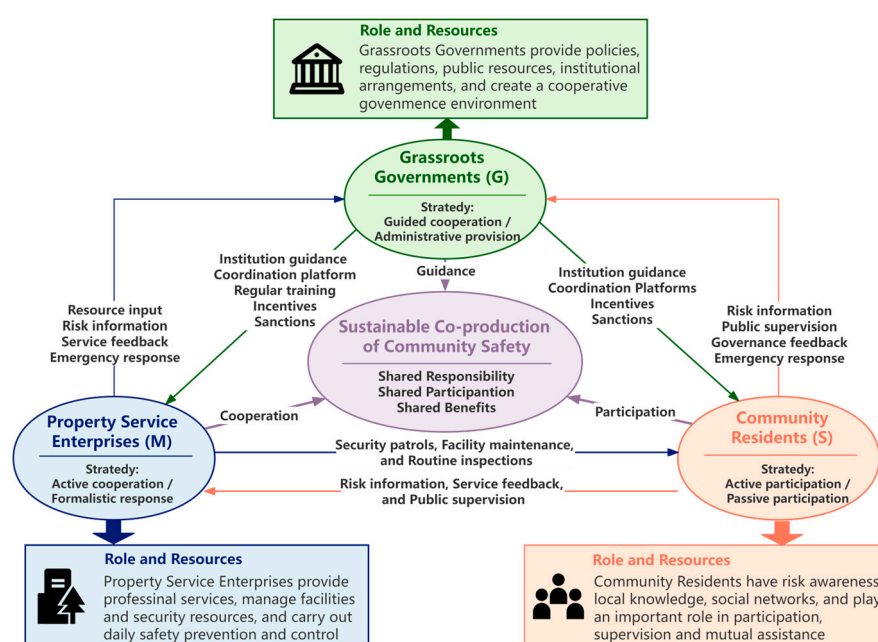


Figure 1. Interaction process among grassroots governments, PSEs, and community residents.

Based on the above analysis, this study aims to construct a tripartite game model, determine the payoff structures of grassroots governments, PSEs, and community residents, simulate the interactions among the three actors, and explain their cooperative behavior characteristics and strategic choices.

3.1. Model Assumptions

According to evolutionary game theory, each player is a boundedly rational individual who possesses different strategies (cooperation and defection), with varying probabilities and payoffs [46]. Each player adjusts its strategy based on the corresponding payoff outcomes [47]. Considering the evolutionary game approach, previous studies on co-production involving governments, market actors, and the public, as well as practical governance contexts [9,22,31–35], this study incorporates variables including payoffs, costs, incentives, sanctions, and information transparency into the model assumptions and payoff parameters (Table 1). The following assumptions are proposed.

Table 1. Definitions of the main parameters.

Actors	Parameter	Definition
Parameters related to grassroots governments	R_g	Governance benefits obtained by grassroots governments when both PSEs and community residents actively participate
	R_{g1}	Governance benefits obtained by grassroots governments when only one of the two actors, either PSEs or community residents, actively participates
	C_{g1}	Organizational costs incurred by grassroots governments when choosing the “guided cooperation” strategy
	C_{g2}	Administrative provision costs incurred by grassroots governments when choosing the “administrative provision” strategy
	I_m	Recognition and incentives provided by grassroots governments to PSEs that actively cooperate
	I_s	Recognition and incentives provided by grassroots governments to community residents who actively participate in governance
	F_m	Sanctions imposed by grassroots governments on PSEs that adopt a formalistic response or fail to fulfill their responsibilities
	F_s	Sanctions imposed by grassroots governments on community residents who violate community safety rules, such as illegal electric-wire charging
Parameters related to PSEs	R_m	Reputational and material benefits obtained by PSEs after actively participating in community safety governance
	C_{m1}	Security-related costs incurred by PSEs when choosing the “active cooperation” strategy
	C_{m2}	Operating costs incurred by PSEs when choosing the “formalistic response” strategy
	D_m	Opportunistic gains obtained by PSEs under the “formalistic response” strategy
Parameters related to community residents	R_s	Safety utility obtained by community residents after actively participating in community safety governance
	C_s	Time and effort costs incurred by community residents when actively participating in community safety governance
	D_s	Free-riding benefits obtained by community residents under the “passive participation” strategy
Common parameters	T	Governance cost savings generated by social capital
	θ	Probability that information transparency enables the detection and sanctioning of violations
	α_2	Conversion coefficient of social capital when two actors cooperate
	α_3	Conversion coefficient of social capital when all three actors cooperate

Assumption 1. In community safety governance, the governance actors comprise grassroots governments (G), PSEs (M), and community residents (S), all of which are boundedly rational game players. Under conditions of incomplete information, limited cognitive capacity, and a complex governance environment, these actors cannot make fully optimal decisions at the initial stage. Instead, they continuously adjust their strategies according to relative payoffs through repeated interactions, and the system may eventually converge to an evolutionary stable state.

Assumption 2. In community safety governance, grassroots governments (G) choose between “guided cooperation” and “administrative provision” with probabilities x ($0 \leq x \leq 1$) and $1 - x$, respectively. “Guided cooperation” refers to the strategy whereby grassroots governments guide PSEs and community residents to participate in community safety governance by establishing deliberative platforms, mobilizing actors, providing incentives, and imposing constraints. “Administrative provision” refers to the strategy whereby grassroots governments rely on administrative authority to dominate community safety governance and bear its major costs and responsibilities. PSEs (M) choose between “active cooperation” and “formalistic response” with probabilities

y ($0 \leq y \leq 1$) and $1 - y$, respectively. “Active cooperation” means that PSEs make substantive investments in security personnel, public facility maintenance, and safety hazard inspections. “Formalistic response” means that PSEs provide only superficial cooperation and are unwilling to bear substantive governance costs. Community residents (S) choose between “active participation” and “passive participation” with probabilities z ($0 \leq z \leq 1$) and $1 - z$, respectively. “Active participation” includes reporting safety hazards, participating in safety deliberation, cooperating in emergency drills, and engaging in public oversight. “Passive participation” refers to free-riding or indifference toward community safety affairs.

Assumption 3. In terms of payoffs, PSEs and community residents can obtain benefits from actively participating in community safety governance. PSEs can obtain additional benefits R_m from improved community safety conditions, including increased recognition from governments, enhanced corporate reputation, improved service evaluations, and higher property fee collection rates. Community residents can obtain direct safety utility R_s from improved protection of life and property security, better living environments, and more rapid resolution of safety issues. Grassroots governments can obtain governance benefits R_g from the active participation of both PSEs and community residents, including reduced governance pressure, lower risks, and enhanced residents’ sense of safety and satisfaction. If only one of PSEs or community residents participates actively, grassroots governments obtain a relatively lower benefit R_{g1} . If neither participates, the additional governance benefit obtained by grassroots governments is assumed to be 0. Meanwhile, when PSEs adopt the strategy of symbolic compliance, they can obtain opportunistic benefits D_m by reducing additional governance costs. When community residents choose passive participation, they can obtain free-riding benefits D_s .

Assumption 4. In terms of costs, when grassroots governments choose “guided cooperation”, they incur organizational costs C_{g1} associated with establishing deliberation platforms, providing safety training, and undertaking supervision responsibilities. When they choose “administrative provision”, they bear higher direct governance costs C_{g2} , where $C_{g2} > C_{g1}$, because grassroots governments need to rely more heavily on law enforcement personnel and public resources to address community safety issues. When PSEs choose “active cooperation”, they need to conduct routine risk inspections, information reporting, personnel management, and emergency response activities, thereby incurring higher costs in terms of human resources, financial inputs, and time investments C_{m1} . When they choose “formalistic response”, they only need to bear routine operational costs C_{m2} , where $C_{m1} > C_{m2}$. When community residents choose “active participation”, they incur participation costs C_s arising from safety deliberation, cooperation in emergency response, and supervision of community affairs. According to social capital theory, multi-actor cooperation can effectively reduce communication and transaction costs among groups and organizations [48,49]. This study assumes that when the stock of social capital reaches a certain level, it generates the maximum cost-saving effect T . A social capital conversion coefficient α_i ($i = 2, 3$) is introduced to represent the extent to which accumulated social capital is converted into governance cost savings under different levels of cooperation. When two actors simultaneously adopt active strategies, the cost-saving effect is $\alpha_2 T$; when all three actors adopt active strategies, the cost-saving effect is $\alpha_3 T$, where $0 < \alpha_2 < \alpha_3 < 1$.

Assumption 5. In terms of incentives and sanctions, when grassroots governments choose “guided cooperation”, they provide material or symbolic incentives I_m and I_s to PSEs and community residents, respectively. These incentives include financial subsidies, recognition awards, honorary titles, and other material or symbolic rewards. When PSEs adopt “formalistic response”, grassroots governments impose sanctions F_m , including inspection criticism, performance deductions, and regulatory penalties. If community residents violate community safety rules or fail to fulfill specific obligations, they may face sanctions F_s , such as penalties for violations. Since PSEs and community residents undertake different levels of formal and contractual responsibilities, this study assumes

that $F_m > F_s$. Based on information asymmetry theory, information transparency enables grassroots governments to identify more easily the passive behavior of other actors or behaviors that undermine community safety [50]. Therefore, this study introduces the information transparency coefficient θ ($0 < \theta < 1$). The actual expected sanctions faced by PSEs and community residents are θF_m and θF_s , respectively. If grassroots governments choose administrative provision, the above incentives and sanctions are not triggered.

3.2. Evolutionary Game Model Analysis

Based on these assumptions, the payoffs of grassroots governments, PSEs, and community residents under different strategy combinations are summarized in Table 2.

Table 2. Payoff matrix of the tripartite evolutionary game.

Strategy Combination	Payoff of Grassroots Governments	Payoff of PSEs	Payoff of Community Residents
(1, 1, 1)	$R_g - C_{g1} - I_m - I_s + \alpha_3 T$	$R_m - C_{m1} + I_m + \alpha_3 T$	$R_s - C_s + I_s + \alpha_3 T$
(1, 1, 0)	$R_{g1} - C_{g1} - I_m + \theta F_s + \alpha_2 T$	$R_m - C_{m1} + I_m + \alpha_2 T$	$D_s - \theta F_s$
(1, 0, 1)	$R_{g1} - C_{g1} - I_s + \theta F_m + \alpha_2 T$	$D_m - C_{m2} - \theta F_m$	$R_s - C_s + I_s + \alpha_2 T$
(1, 0, 0)	$-C_{g1} + \theta F_m + \theta F_s$	$D_m - C_{m2} - \theta F_m$	$D_s - \theta F_s$
(0, 1, 1)	$R_g - C_{g2}$	$R_m - C_{m1} + \alpha_2 T$	$R_s - C_s + \alpha_2 T$
(0, 1, 0)	$R_{g1} - C_{g2}$	$R_m - C_{m1}$	D_s
(0, 0, 1)	$R_{g1} - C_{g2}$	$D_m - C_{m2}$	$R_s - C_s$
(0, 0, 0)	$-C_{g2}$	$D_m - C_{m2}$	D_s

Using the payoff matrix in Table 2, we derive the expected payoffs, average payoffs, and replicator dynamic equations for grassroots governments, PSEs, and community residents.

(1) The expected payoffs of grassroots governments choosing guided cooperation, the expected payoffs and administrative provision are denoted by E_{g1} and E_{g2} , respectively, and their average expected payoff is denoted by $\bar{E}_g$.

$$E_{g1} = R_{g1} - C_{g1} + yz(R_g - R_{g1} + \alpha_3 T - \alpha_2 T) + y(-I_m + \theta F_s - \theta F_m + \alpha_2 T) + z(-I_s + \theta F_m - \theta F_s + \alpha_2 T) + \theta F_m + \theta F_s \quad (1)$$

$$E_{g2} = R_{g1} - C_{g2} + yz(R_g - R_{g1}) \quad (2)$$

$$\bar{E}_g = xE_{g1} + (1 - x)E_{g2} \quad (3)$$

(2) The expected payoffs of PSEs choosing active cooperation and a formalistic response are denoted by E_{m1} and E_{m2} , respectively, and their average expected payoff is denoted by $\bar{E}_m$.

$$E_{m1} = R_m - C_{m1} + xI_m + \alpha_2 T(x + z) + (\alpha_3 - 2\alpha_2)Txz \quad (4)$$

$$E_{m2} = D_m - C_{m2} - x\theta F_m \quad (5)$$

$$\bar{E}_m = yE_{m1} + (1 - y)E_{m2} \quad (6)$$

(3) The expected payoffs of community residents choosing active participation and passive participation are denoted by E_{s1} and E_{s2} , respectively, and their average expected payoff is denoted by $\bar{E}_s$.

$$E_{s1} = R_s - C_s + xI_s + \alpha_2 T(x + y) + (\alpha_3 - 2\alpha_2)Txy \quad (7)$$

$$E_{s2} = D_s - x\theta F_s \quad (8)$$

$$\bar{E}_s = zE_{s1} + (1 - z)E_{s2} \quad (9)$$

Accordingly, the replicator dynamic equations governing the strategic evolution of grassroots governments, PSEs, and community residents can be written as follows:

$$F(x) = x(E_{g1} - \bar{E}_g) = \frac{dx}{dt} = x(1 - x)[C_{g2} - C_{g1} - yI_m - zI_s + (1 - y)\theta F_m + (1 - z)\theta F_s + \alpha_2 T(y + z) + (\alpha_3 - 2\alpha_2)Tyz] \quad (10)$$

$$F(y) = y(E_{m1} - \bar{E}_m) = \frac{dy}{dt} = y(1 - y)[R_m - (C_{m1} - C_{m2}) - D_m + x(I_m + \theta F_m) + \alpha_2 T(x + z) + (\alpha_3 - 2\alpha_2)Txz] \quad (11)$$

$$F(z) = z(E_{s1} - \bar{E}_s) = \frac{dz}{dt} = z(1 - z)[R_s - C_s - D_s + x(I_s + \theta F_s) + \alpha_2 T(x + y) + (\alpha_3 - 2\alpha_2)Txy] \quad (12)$$

4. Equilibrium and Stability Analysis

4.1. Stability Analysis of Grassroots Government Strategies

Based on Equation (13), the first-order derivative of the grassroots governments' replicator dynamic equation with respect to x is given by:

$$\frac{dF(x)}{dx} = (1 - 2x)[C_{g2} - C_{g1} - yI_m - zI_s + (1 - y)\theta F_m + (1 - z)\theta F_s + \alpha_2 T(y + z) + (\alpha_3 - 2\alpha_2)Tyz] \quad (13)$$

(1) When $y = \frac{-C_{g2} + C_{g1} - \theta F_m - \theta F_s + zI_s + z\theta F_s - z\alpha_2 T}{-I_m - \theta F_m + \alpha_2 T + zT(\alpha_3 - 2\alpha_2)} = y^*$, $0 < y^* < 1$, the replicator dynamic equation satisfies $F(x) = 0$. In this case, regardless of the value of x , the strategy of grassroots governments remains in a critical state, and the probability of choosing either guided cooperation or administrative provision does not change over time.

(2) When $0 < y < y^* < 1$, $\frac{dF(x)}{dx}|_{x=0} < 0$, $\frac{dF(x)}{dx}|_{x=1} > 0$, $x = 0$ is the evolutionarily stable strategy for grassroots governments; that is, grassroots governments choose administrative provision.

(3) When $0 < y^* < y < 1$, $\frac{dF(x)}{dx}|_{x=0} > 0$, $\frac{dF(x)}{dx}|_{x=1} < 0$, $x = 1$ is the evolutionarily stable strategy for grassroots governments; that is, grassroots governments choose guided cooperation.

4.2. Stability Analysis of Property Service Enterprise Strategies

Based on Equation (14), the first-order derivative of the PSEs' replicator dynamic equation with respect to y is given by:

$$\frac{dF(y)}{dy} = (1 - 2y)[R_m + x(I_m + \theta F_m) - (C_{m1} - C_{m2}) - D_m + \alpha_2 T(x + z) + (\alpha_3 - 2\alpha_2)Txz] \quad (14)$$

(1) When $x = \frac{-R_m + D_m + C_{m1} - C_{m2} - z\alpha_2 T}{I_m + \theta F_m + \alpha_2 T + zT(\alpha_3 - 2\alpha_2)} = x^*$, $0 < x^* < 1$, the replicator dynamic equation satisfies $F(y) = 0$. In this case, regardless of the value of y , the strategy of PSEs remains in a critical state, and the probability of choosing either active cooperation or a formalistic response does not change over time.

(2) When $0 < x < x^* < 1$, $\frac{dF(y)}{dy}|_{y=0} < 0$, $\frac{dF(y)}{dy}|_{y=1} > 0$, $y = 0$ is the evolutionarily stable strategy for PSEs; that is, PSEs choose a formalistic response.

(3) When $0 < x^* < x < 1$, $\frac{dF(y)}{dy}|_{y=0} > 0$, $\frac{dF(y)}{dy}|_{y=1} < 0$, $y = 1$ is the evolutionarily stable strategy for PSEs; that is, PSEs choose active cooperation.

4.3. Stability Analysis of Community Resident Strategies

Based on Equation (15), the first-order derivative of the community residents' replicator dynamic equation with respect to z is given by:

$$\frac{dF(z)}{dz} = (1 - 2z)[R_s + x(I_s + \theta F_s) - C_s - D_s + \alpha_2 T(x + y) + (\alpha_3 - 2\alpha_2)Txy] \quad (15)$$

(1) When $x = \frac{-R_s + D_s + C_s - y\alpha_2 T}{I_s + \theta F_s + \alpha_2 T + yT(\alpha_3 - 2\alpha_2)} = x^*$, $0 < x^* < 1$, the replicator dynamic equation satisfies $F(z) = 0$. In this case, regardless of the value of z , the strategy of community residents remains in a critical state, and the probability of choosing either active participation or passive participation does not change over time.

(2) When $0 < x < x^* < 1$, $\frac{dF(z)}{dz}|_{z=0} < 0$, $\frac{dF(z)}{dz}|_{z=1} > 0$, $z = 0$ is the evolutionarily stable strategy for community residents; that is, community residents choose passive participation.

(3) When $0 < x^* < x < 1$, $\frac{dF(z)}{dz}|_{z=0} > 0$, $\frac{dF(z)}{dz}|_{z=1} < 0$, $z = 1$ is the evolutionarily stable strategy for community residents; that is, community residents choose active participation.

4.4. Stability Analysis of Equilibrium Points in the Evolutionary Game Model

Building on the strategy stability analysis of grassroots governments, PSEs, and community residents, the three replicator dynamic equations are further solved jointly. According to Ritzberger and Weibull [51], it is sufficient to examine the evolutionary stability of the eight pure-strategy equilibrium points: $E_1(0, 0, 0)$, $E_2(1, 0, 0)$, $E_3(0, 1, 0)$, $E_4(0, 0, 1)$, $E_5(1, 1, 0)$, $E_6(1, 0, 1)$, $E_7(0, 1, 1)$, and $E_8(1, 1, 1)$. The stability of the equilibrium points in the evolutionary game model is assessed by analyzing the Jacobian matrix J , as shown in Equation (16).

$$J = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z} \\ \frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z} \end{bmatrix} = \begin{bmatrix} J_{11} & J_{12} & J_{13} \\ J_{21} & J_{22} & J_{23} \\ J_{31} & J_{32} & J_{33} \end{bmatrix} \quad (16)$$

The expressions of the elements in the Jacobian matrix J are given as follows:

$$\left\{ \begin{array}{l} J_{11} = (1 - 2x)[C_{g2} - C_{g1} - yI_m - zI_s + (1 - y)\theta F_m + (1 - z)\theta F_s + \alpha_2 T(y + z) + (\alpha_3 - 2\alpha_2)Ty] \\ J_{12} = x(1 - x)[-I_m - \theta F_m + \alpha_2 T + (\alpha_3 - 2\alpha_2)Tz] \\ J_{13} = x(1 - x)[-I_s - \theta F_s + \alpha_2 T + (\alpha_3 - 2\alpha_2)Ty] \\ J_{21} = y(1 - y)[I_m + \theta F_m + \alpha_2 T + (\alpha_3 - 2\alpha_2)Tz] \\ J_{22} = (1 - 2y)[R_m - (C_{m1} - C_{m2}) - D_m + x(I_m + \theta F_m) + \alpha_2 T(x + z) + (\alpha_3 - 2\alpha_2)Tx] \\ J_{23} = y(1 - y)[R_m + \alpha_2 T + (\alpha_3 - 2\alpha_2)Tx] \\ J_{31} = z(1 - z)[I_s + \theta F_s + \alpha_2 T + (\alpha_3 - 2\alpha_2)Ty] \\ J_{32} = z(1 - z)[I_s + \theta F_s + \alpha_2 T + (\alpha_3 - 2\alpha_2)Ty] \\ J_{33} = (1 - 2z)[R_s - C_s - D_s + x(I_s + \theta F_s) + \alpha_2 T(x + y) + (\alpha_3 - 2\alpha_2)Tx] \end{array} \right. \quad (17)$$

According to Lyapunov's first method, an equilibrium point is asymptotically stable if all eigenvalues of the Jacobian matrix have negative real parts. If at least one eigenvalue has a positive real part, the equilibrium point is unstable. If the Jacobian matrix has eigenvalues with zero real parts and all the remaining eigenvalues have negative real parts, the equilibrium point is in a critical state, and its stability cannot be determined solely by the signs of the eigenvalues [52]. Each equilibrium point is substituted into the Jacobian matrix to obtain the corresponding eigenvalues, and the stability of each equilibrium point is analyzed accordingly, as presented in Tables 3 and 4. Among these equilibrium points, the realization of the optimal cooperative state $E_8(1,1,1)$ requires the simultaneous satisfaction of three conditions: $I_m + I_s < C_{g2} - C_{g1} + \alpha_3 T$, $R_m + I_m + \theta F_m + \alpha_3 T + C_{m2} > D_m + C_{m1}$ and $R_s + I_s + \theta F_s + \alpha_3 T > C_s + D_s$. Under these conditions, for grassroots governments, the total incentives provided to PSEs and community residents should not exceed the difference in costs between administrative provision and guided cooperation, together with the cost-saving effects generated by three-party cooperation. For PSEs, the additional safety-related benefits, government incentives, expected sanction pressure, and cost-saving effects from social capital should be sufficient to compensate for the costs of active cooperation and the loss of opportunistic benefits. For community residents, the direct safety utility,

government incentives, expected sanction pressure, and cost-saving effects from social capital should be sufficient to offset the costs of active participation and free-riding benefits. These conditions indicate that the stable realization of community safety co-production does not depend on the unilateral action of any single actor. Instead, it requires government incentives, information transparency, sanction constraints, and social capital to jointly reshape the payoff structures of the three actors, enabling the system to evolve gradually from low-level states such as administrative provision, formalistic response, and passive participation toward a tripartite collaborative governance state.

Table 3. Stability analysis of equilibrium points.

Equilibrium Points	Eigenvalues of the Jacobian Matrix		
	λ_1	λ_2	λ_3
$E_1(0,0,0)$	$C_{g2} - C_{g1} + \theta F_m + \theta F_s$	$R_m - (C_{m1} - C_{m2}) - D_m$	$R_s - C_s - D_s$
$E_2(1,0,0)$	$-(C_{g2} - C_{g1} + \theta F_m + \theta F_s)$	$R_m - (C_{m1} - C_{m2}) - D_m + I_m + \theta F_m + \alpha_2 T$	$R_s - C_s - D_s + I_s + \theta F_s + \alpha_2 T$
$E_3(0,1,0)$	$C_{g2} - C_{g1} - I_m + \theta F_s + \alpha_2 T$	$-(R_m - C_{m1} + C_{m2} - D_m)$	$R_s - C_s - D_s + \alpha_2 T$
$E_4(0,0,1)$	$C_{g2} - C_{g1} - I_s + \theta F_m + \alpha_2 T$	$R_m - (C_{m1} - C_{m2}) - D_m + \alpha_2 T$	$-(R_s - C_s - D_s)$
$E_5(1,1,0)$	$-(C_{g2} - C_{g1} - I_m + \theta F_s + \alpha_2 T)$	$-[R_m - (C_{m1} - C_{m2}) - D_m + I_m + \theta F_m + \alpha_2 T]$	$R_s - C_s - D_s + I_s + \theta F_s + \alpha_2 T$
$E_6(1,0,1)$	$-(C_{g2} - C_{g1} - I_s + \theta F_m + \alpha_2 T)$	$R_m - (C_{m1} - C_{m2}) - D_m + I_m + \theta F_m + \alpha_3 T$	$-(R_s - C_s - D_s + I_s + \theta F_s + \alpha_2 T)$
$E_7(0,1,1)$	$C_{g2} - C_{g1} - I_m - I_s + \alpha_3 T$	$-[R_m - (C_{m1} - C_{m2}) - D_m + \alpha_2 T]$	$-(R_s - C_s - D_s + \alpha_2 T)$
$E_8(1,1,1)$	$-(C_{g2} - C_{g1} - I_m - I_s + \alpha_3 T)$	$-[R_m - (C_{m1} - C_{m2}) - D_m + I_m + \theta F_m + \alpha_3 T]$	$-(R_s - C_s - D_s + I_s + \theta F_s + \alpha_3 T)$

Table 4. Stability conditions of equilibrium points.

Points	Stability Conditions
$E_1(0,0,0)$	Unstable point
$E_2(1,0,0)$	$R_m + I_m + C_{m2} + \theta F_m + \alpha_2 T < D_m + C_{m1}$ and $R_s + I_s + \theta F_s + \alpha_2 T < -C_s + D_s$
$E_3(0,1,0)$	$I_m > C_{g2} - C_{g1} + \theta F_s + \alpha_2 T$, $R_m + C_{m2} > D_m + C_{m1}$ and $R_s + \alpha_2 T < C_s + D_s$
$E_4(0,0,1)$	$I_s > C_{g2} - C_{g1} + \theta F_m + \alpha_2 T$, $R_m + \alpha_2 T + C_{m2} < D_m + C_{m1}$ and $R_s > C_s + D_s$
$E_5(1,1,0)$	$I_m < C_{g2} - C_{g1} + \theta F_s + \alpha_2 T$, $R_m + I_m + \theta F_m + \alpha_2 T + C_{m2} > D_m + C_{m1}$ and $R_s + I_s + \theta F_s + \alpha_2 T < C_s + D_s$
$E_6(1,0,1)$	$I_s < C_{g2} - C_{g1} + \theta F_m + \alpha_2 T$, $R_m + I_m + \theta F_m + \alpha_3 T + C_{m2} < D_m + C_{m1}$ and $R_s + I_s + \theta F_s + \alpha_2 T > C_s + D_s$
$E_7(0,1,1)$	$I_m + I_s > C_{g2} - C_{g1} + \alpha_3 T$, $R_m + \alpha_2 T + C_{m2} > D_m + C_{m1}$ and $R_s + \alpha_2 T > C_s + D_s$
$E_8(1,1,1)$	$I_m + I_s < C_{g2} - C_{g1} + \alpha_3 T$, $R_m + I_m + \theta F_m + \alpha_3 T + C_{m2} > D_m + C_{m1}$ and $R_s + I_s + \theta F_s + \alpha_3 T > C_s + D_s$

5. Simulation Analysis of the Evolutionary Game

Theoretical derivation alone cannot intuitively reveal how different parameters affect the evolutionary stability of the game system. To better understand the strategic choices and behavioral evolution of the three actors in community safety co-production, this study uses MATLAB R2025b to simulate the evolutionary process of the tripartite evolutionary game model. The simulations are designed to examine the initial willingness of grassroots governments, PSEs, and community residents, as well as the effects of key parameters on the strategic evolution of each actor.

5.1. Case Background and Parameter Assignment

To examine the effectiveness of the stability analysis of the evolutionary model, this study conducts numerical simulations. To ensure the rationality and feasibility of the parameter settings, the benchmark parameters are assigned by referring to the treatment of parameter settings in existing studies [53–55], the case materials of the PDC in Changsha, and the opinions of practitioners and experts in the field of community safety. It should be noted that the parameter assignment in this study is not intended to precisely measure the actual fiscal expenditures of the Changsha PDC practice, the specific benefits obtained by PSEs, or the utility gains of community residents. Rather, the purpose is to conduct a contextualized simulation of the tripartite strategic evolution mechanism under assumptions that are consistent with practical experience and theoretical reasoning. Based on the above considerations, the benchmark parameters are set as follows: $C_{g1} = 6$, $C_{g2} = 10$, $I_m = 1.5$, $I_s = 1$, $F_m = 3$, $F_s = 2$, $C_{m1} = 6$, $C_{m2} = 2$, $R_m = 4$, $D_m = 1.5$, $C_s = 3$, $R_s = 5$, $D_s = 2.5$, $\theta = 0.7$, $T = 5$, $\alpha_2 = 0.3$, and $\alpha_3 = 0.8$. These parameter settings reflect the basic assumptions that the cost of administrative provision by grassroots governments is higher than that of guided cooperation, the cost of active cooperation by PSEs is higher than that of formalistic response, and the social capital conversion rate under tripartite cooperation is higher than that under two-party cooperation.

5.2. Simulation Analysis of the Overall Evolutionary System

An in-depth analysis of the strategic choices and interactions among stakeholders can reveal the behavioral characteristics of different actors in the co-production process. These characteristics help explain the internal logic of multi-actor interaction and the dynamic changes in the degree of cooperation among actors. As shown in Figure 2, the strategic choices of the three actors eventually converge toward a unified state: grassroots governments tend to choose guided cooperation, PSEs tend to choose active cooperation, and community residents tend to actively participate in community safety co-production.

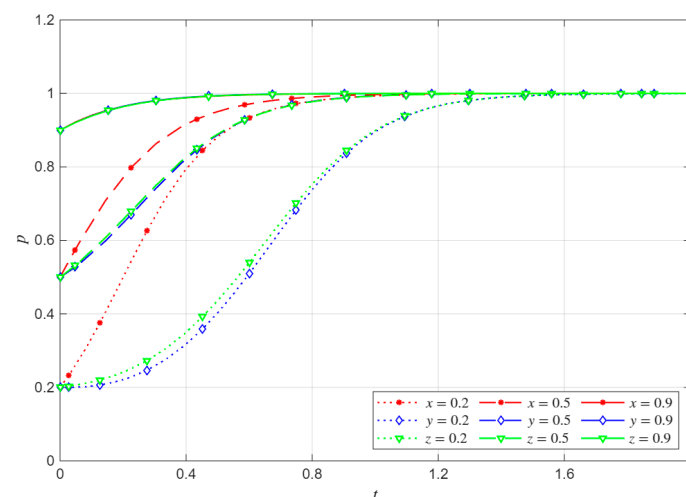


Figure 2. Evolutionary trends of strategies under different initial values.

The initial probabilities of the three actors are set at 0.2, 0.5, and 0.9, respectively, while the remaining parameters are kept unchanged. The evolutionary process of actor strategies is then observed. The results show that, as the initial probability increases, the system converges to 1 more rapidly, and the strategic evolution of the actors exhibits clear differences across different initial states. As the willingness and actions of grassroots governments to guide cooperation increase, the participation of community residents is significantly strengthened. By contrast, PSEs are more cautious in their strategic choices.

This evolutionary pattern suggests that the decision-making of PSEs is essentially an adaptive response to their surrounding environment and community consensus. Their strategic responsiveness is lower than that of grassroots governments and community residents, reflecting the risk-avoidance tendency of market actors. The results also indicate that stronger government guidance can generate a positive feedback loop of “government guidance–resident response–enterprise follow-up”, thereby substantially shortening the convergence time of the game system.

To further examine the strategic choices of the actors, the initial willingness of grassroots governments, PSEs, and community residents is set as (0.5, 0.5, 0.5). The evolutionary process of the three actors is shown in Figure 3. The results indicate that the degree of cooperation among the actors changes across different stages of system evolution. In the early stage, the cooperative foundation among community actors is weak, effective coordination and cooperation have not yet been formed, and free-riding tendencies are common. In the middle stage, after repeated interactions, especially under the guidance of grassroots governments, the actors gradually develop more complete interaction mechanisms and achieve a certain degree of cooperation. In the later stage, a multilateral reciprocal network is formed, and the sharing of benefits and risks further deepens co-production. The system then enters a self-reinforcing stable state and reaches the equilibrium point (1, 1, 1), indicating a transition from a loosely connected state to a closely coordinated collaborative state.

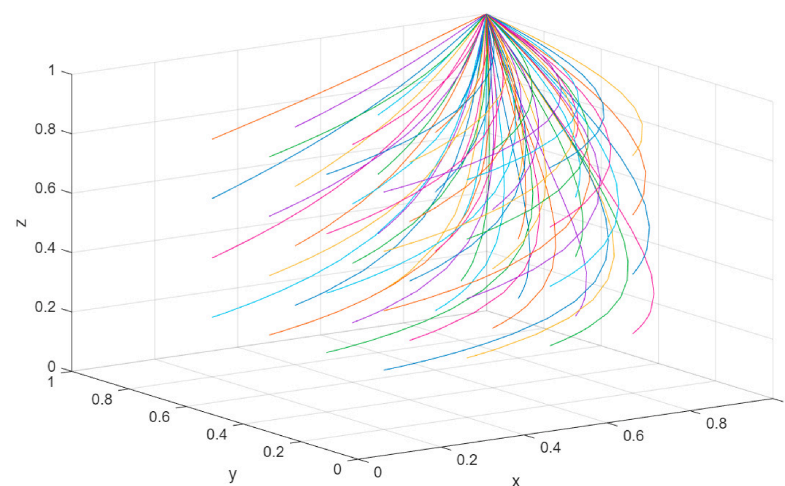


Figure 3. Evolutionary path of the tripartite game system under the initial values.

5.3. Sensitivity Analysis of the Main Influencing Factors

5.3.1. Effects of Government Incentives on Strategy Evolution

To promote sustainable community safety co-production, grassroots governments initially provide incentives to encourage other actors to actively participate. Motivation crowding theory suggests that government incentives may influence individual and organizational behaviors, but excessive or inappropriate incentives may undermine intrinsic motivation and distort participation behaviors [56]. To examine the strategy evolution of the three actors under different incentive intensities, this section holds all other parameters constant and adjusts only the incentives provided by the government to PSEs and community residents. Four scenarios are established: low incentives ($I_m = 0.3$, $I_s = 0.2$), moderate incentives ($I_m = 1.5$, $I_s = 1.0$), relatively high incentives ($I_m = 3.0$, $I_s = 2.0$) and excessive incentives ($I_m = 4.5$, $I_s = 3.0$). The low-incentive scenario represents insufficient government incentives; the moderate-incentive scenario represents an incentive level within a reasonable range; the relatively high-incentive scenario indicates that the total incentive level approaches the government’s cost-bearing threshold; and the excessive-incentive

scenario indicates that the total incentive level exceeds the government's affordable range. By comparing the evolutionary trajectories of x , y and z across these scenarios, this section assesses how government incentive intensity affects the speed and stability of tripartite collaborative governance formation, as shown in Figure 4.

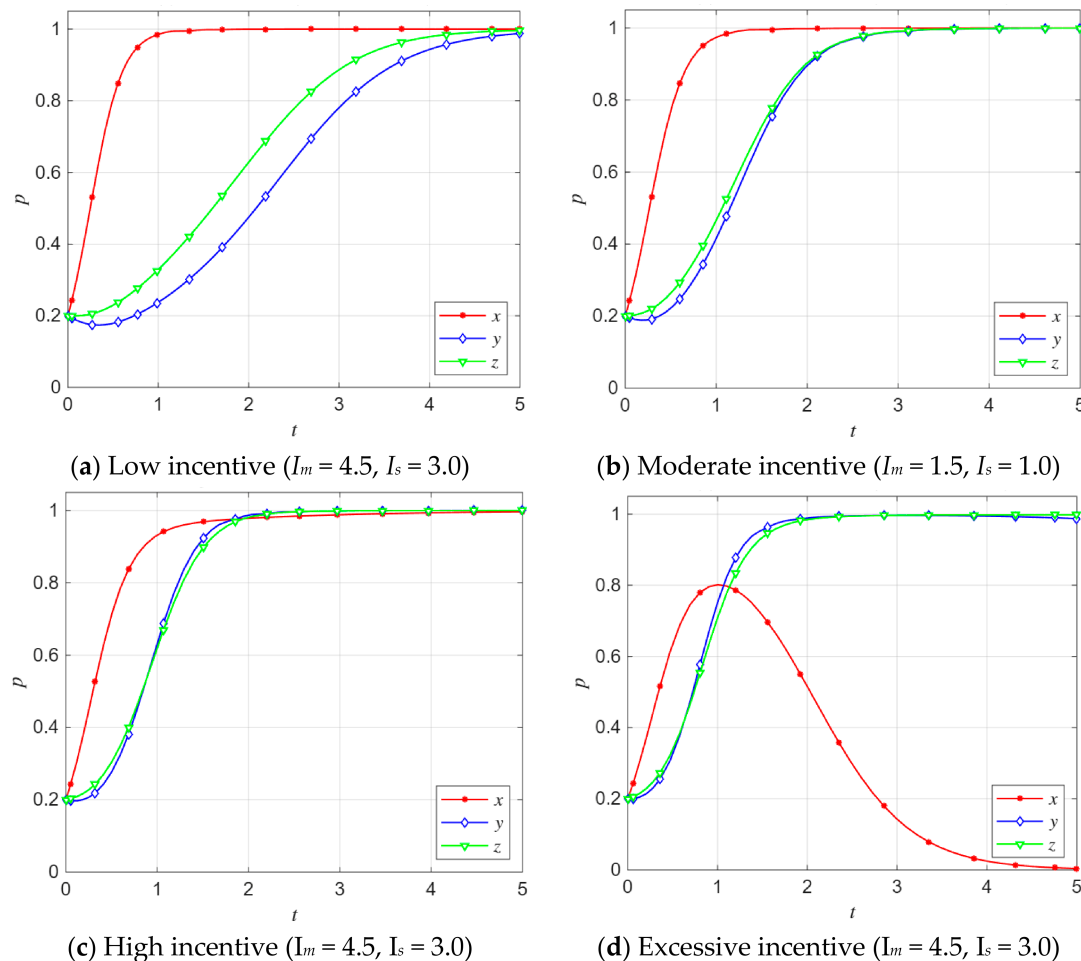


Figure 4. Effects of changes in government incentives on system evolution.

The simulation results show that government incentives have a dual effect on system evolution. Under the low-incentive scenario, PSEs and community residents lack sufficient motivation to choose active strategies, and the system evolves slowly toward collaborative governance. Under the moderate-incentive scenario, government incentives effectively compensate for the costs of active cooperation by PSEs and the participation costs of community residents, enabling the three actors to converge more rapidly toward a collaborative state characterized by guided cooperation, active cooperation, and active participation. Under the relatively high-incentive scenario, the motivation of PSEs and community residents is further strengthened, but the incentive burden on grassroots governments begins to increase. When incentive intensity becomes excessive, the total incentive expenditure exceeds the combined cost savings generated by replacing administrative provision with guided cooperation and by social capital, thereby weakening the motivation of grassroots governments to continue choosing guided cooperation. These findings indicate that government incentives are not more effective simply because they are higher; rather, they should be maintained within an appropriate range. Moderate incentives can stimulate the participation of PSEs and community residents, whereas excessive incentives may impose

an excessive cost burden on governments and undermine the sustainability of community safety co-production.

5.3.2. Effects of Information Transparency and Sanction Intensity on System Evolution

According to deterrence theory, the effectiveness of sanctions depends not only on the severity of punishment imposed after misconduct is detected but also on the probability that such misconduct will be detected [57,58]. Therefore, to examine the effects of information transparency and sanction intensity on mitigating opportunistic behaviors, this section focuses on the impacts of θF_m and θF_s on PSEs' active cooperation and community residents' active participation. Four combinations of information transparency and sanction intensity are considered: low transparency–low sanctions ($\theta = 0.2, F_m = 0.5, F_s = 0.25$), low transparency–high sanctions ($\theta = 0.2, F_m = 4.0, F_s = 2.0$), high transparency–low sanctions ($\theta = 0.8, F_m = 0.5, F_s = 0.25$), and high transparency–high sanctions ($\theta = 0.8, F_m = 4.0, F_s = 2.0$). The strategy evolution trajectories of the three actors are then analyzed to compare how different combinations of information identification capacity and sanction intensity affect system evolution, as shown in Figure 5.

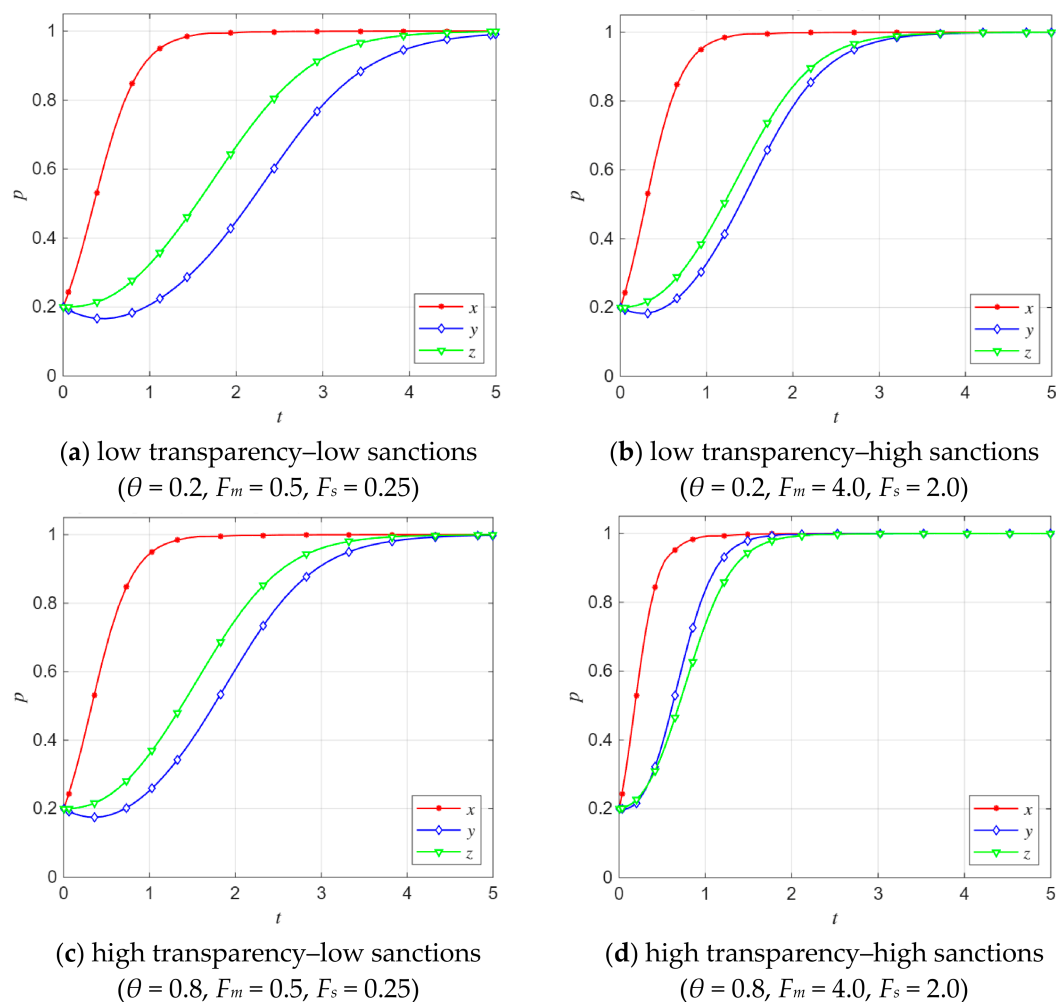


Figure 5. Effects of combined changes in information transparency and sanction intensity on system evolution.

The simulation results show that, under the current parameter settings, all four scenarios can eventually converge toward $E_8(1, 1, 1)$, indicating that the system already has the basic conditions required to evolve toward tripartite collaborative governance. However, the convergence speed differs significantly across different combinations of infor-

mation transparency and sanction intensity. The high-transparency–high-sanction scenario leads the three actors to adopt active strategies most rapidly, suggesting that information transparency and sanction intensity generate a synergistic constraint effect. Information transparency improves the detectability of formalistic responses by PSEs and passive participation by community residents, while sanction intensity increases the opportunistic costs of passive strategies. Together, these two mechanisms accelerate the shift in PSEs and community residents from passive to active strategies. By contrast, under low-transparency conditions, even stronger sanctions may be weakened by insufficient information identification capacity. Under low-sanction conditions, even higher information transparency may not be fully translated into behavioral constraints through disclosure and oversight. These results suggest that the co-production of community safety requires not only stronger accountability but also greater transparency in the governance process through information disclosure, hazard publicity, resident oversight, and deliberative consultation mechanisms, so that sanctions can be transformed into effective constraints.

5.3.3. Effects of Government Incentives and Social Capital on System Evolution

Government incentives, as external incentives for collective action, can enhance the willingness of other actors to participate in community safety co-production. However, such external incentives also increase the costs borne by grassroots governments. In contrast, social capital, as an internal factor embedded in community relationships among stakeholders, can effectively reduce communication, coordination, and transaction costs among co-production participants. Therefore, to further examine the roles of government incentives and social capital in promoting the sustainable co-production of community safety, this section sets four combined scenarios: low incentives–low social capital ($I_m = 0.05$, $I_s = 0.05$, $T = 0.05$), high incentives–low social capital ($I_m = 1.5$, $I_s = 1.0$, $T = 0.05$), low incentives–high social capital ($I_m = 0.05$, $I_s = 0.05$, $T = 2.0$) and high incentives–high social capital ($I_m = 1.5$, $I_s = 1.0$, $T = 2.0$). The evolutionary paths of the three actors' strategies are then analyzed to compare how different combinations of external incentive intensity and social capital level affect the evolutionary outcomes of the system, as shown in Figure 6. Since government incentives mainly increase the expected payoffs of PSEs choosing active cooperation and community residents choosing active participation through I_m and I_s , whereas social capital mainly reduces communication, coordination, and transaction costs among actors through T , this section focuses on how the combined changes in I_m , I_s , and T affect the active cooperation of property enterprises, the active participation of community residents, and the collaborative stability of the system.

The simulation results show that when both government incentives and social capital are low, PSEs and community residents lack sufficient motivation to choose active strategies, and the system evolves slowly toward collaboration. When social capital is low, but government incentives are high, government incentives can partially compensate for the lack of social capital and encourage PSEs and community residents to shift toward active strategies. When government incentives are low, but social capital is high, the system can also move relatively quickly toward collaborative governance. This indicates that social capital can partially substitute for government incentives by reducing communication, coordination, and transaction costs. When both government incentives and social capital are high, the three actors converge most rapidly toward active strategies, suggesting that the two also have a certain complementary effect. These results indicate that the co-production of community safety should not rely on high-intensity government incentives over the long term. Instead, community social capital should be strengthened through deliberative consultation, trust building, information sharing, and the development of

public norms, so as to reduce cooperation costs and enhance the endogenous stability of collaborative governance.

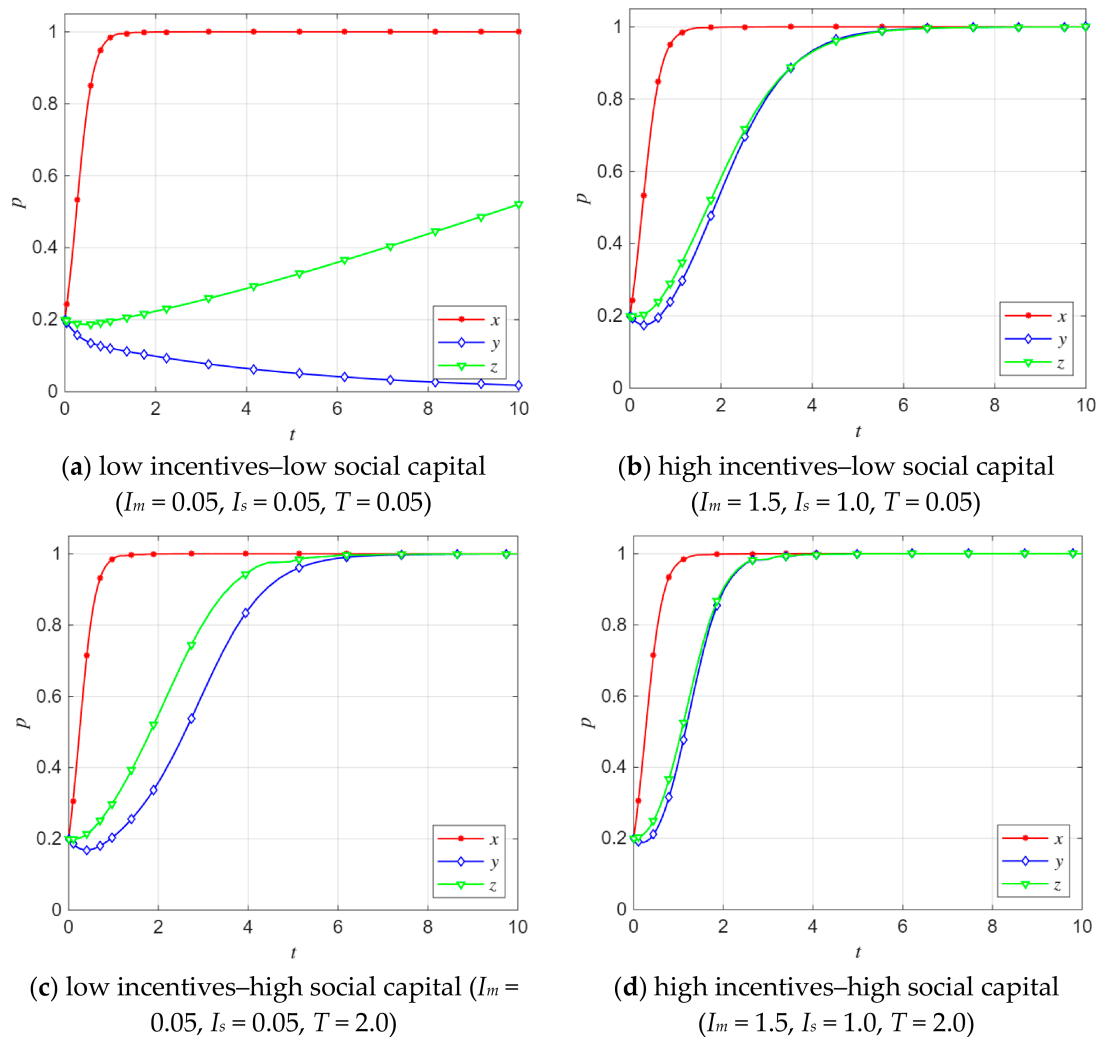


Figure 6. Effects of combined changes in government incentives and social capital on system evolution.

5.3.4. Effects of Social Capital and Opportunistic Gains on System Evolution

In community safety co-production, although PSEs and community residents may consider opportunistic benefits and choose passive strategies, social capital can reduce communication, coordination, and transaction costs among multiple actors through trust, norms, interaction networks, and public deliberation mechanisms, thereby increasing the likelihood that PSEs and community residents adopt active strategies. Therefore, to examine the inhibitory effect of social capital on opportunistic motivation, this section keeps all other parameters unchanged and adjusts only the opportunistic gains D_m and D_s , as well as the social capital effect T . Four scenarios are simulated: low opportunism–low social capital ($D_m = 1.5$, $D_s = 2.5$, $T = 0.2$), high opportunism–low social capital ($D_m = 3.5$, $D_s = 4.5$, $T = 0.2$), high opportunism–high social capital ($D_m = 3.5$, $D_s = 4.5$, $T = 2.2$), and low opportunism–high social capital ($D_m = 1.5$, $D_s = 2.5$, $T = 2.5$), as shown in Figure 7.

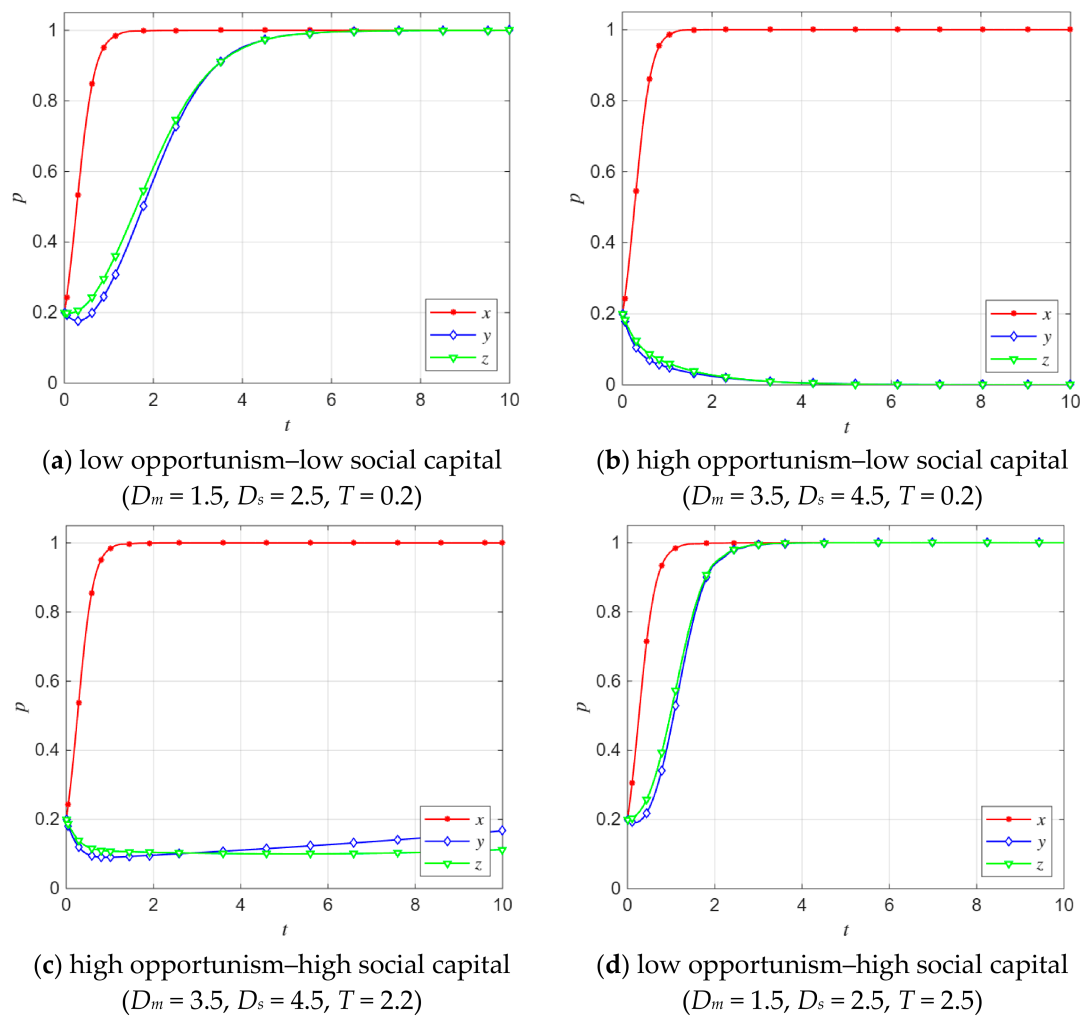


Figure 7. Effects of combined changes in social capital and opportunistic benefits on system evolution.

The simulation results show that, under the low-opportunism–low-social-capital scenario, the system still has a basis for evolving toward collaborative governance because the opportunistic gains of PSEs and community residents are relatively low. However, insufficient social capital leads to higher communication and coordination costs among actors, resulting in a relatively slow convergence speed. Under the high-opportunism–low-social-capital scenario, the payoffs from formalistic responses by PSEs and free-riding by community residents are relatively high, while social capital is insufficient to generate effective constraints. As a result, the system's motivation to evolve toward tripartite collaboration is significantly weakened. By contrast, under the high-opportunism–high-social-capital scenario, although PSEs and community residents still have opportunistic motivations, a higher level of social capital can increase the relative payoff of active strategies by strengthening trust, reinforcing public norms, and reducing transaction costs. This eventually encourages PSEs and community residents to shift toward active strategies. Under the low-opportunism–high-social-capital scenario, the system is most likely to evolve toward $E_8(1, 1, 1)$. These results indicate that social capital has an inhibitory effect on opportunistic behavior. This effect does not operate by directly eliminating opportunistic gains or free-riding benefits. Rather, social capital weakens the attractiveness of opportunistic strategies by reducing cooperation costs, strengthening interactive oversight, and enhancing a shared sense of responsibility, thereby promoting the evolution of community safety co-production toward stable collaboration.

6. Discussion

6.1. Main Findings

Globally, co-production plays an important role in improving community safety. However, under China's governance system, characterized by strong government authority, enterprises and social actors have traditionally been accustomed to passive participation, which creates significant challenges for the development of co-production. To address these challenges, this study draws on the PDC practice in Changsha, Hunan Province, to identify the key actors, functional responsibilities, and institutional arrangements involved in community safety co-production. Based on this practical context, a tripartite evolutionary game model involving grassroots governments, PSEs, and community residents is constructed to further analyze the strategic choices, interactive relationships, and stability conditions of the three actors in community safety co-production. The findings demonstrate that government-guided co-production in the Chinese context is not a form of unilateral administrative mobilization imposed by governments on social actors. Instead, grassroots governments reshape the cost–benefit structures of PSEs and community residents through institutional provision, platform establishment, incentive allocation, information transparency, and accountability constraints. Specifically, these mechanisms increase the expected benefits of active participation, reduce the costs of sustained engagement, and constrain opportunistic benefits, thereby enabling limitedly rational actors to form a co-production arrangement that is sustainable over time, across organizations, and within institutional settings.

First, there are clear strategic linkages among grassroots governments, PSEs, and community residents. The practice of the PDC demonstrates that, when grassroots governments choose “guided cooperation”, they can increase the expected benefits of active strategies for PSEs and community residents through platform building, incentive provision, and accountability constraints. When PSEs choose “active cooperation”, they can improve the community safety environment, enhance governance performance, and strengthen community residents' sense of safety. When community residents choose “active participation”, they can improve risk identification and collaborative response capacity through hazard reporting, public supervision, and safety deliberation. Based on this foundation, the evolutionary game analysis further reveals that when the benefits of active strategies for all three actors exceed those of passive strategies, the system is more likely to evolve toward $E_8(1, 1, 1)$, that is, a stable collaborative state characterized by “guided cooperation by grassroots governments–active cooperation by PSEs–active participation by community residents”. Second, information transparency and sanction intensity generate a synergistic constraint effect. Sanctions do not work independently; rather, their effectiveness is constrained by the level of information transparency. Only when formalistic responses by PSEs and passive participation by community residents can be identified and recorded in a timely manner can sanction intensity be transformed into actual expected sanctions. Therefore, information transparency is a prerequisite for sanction mechanisms to function effectively. Higher information transparency improves the visibility of opportunistic behaviors, while stronger sanctions increase the costs of passive strategies, jointly promoting the transition of PSEs and community residents toward active strategies. Third, government incentives have a dual effect on system evolution. Moderate incentives can increase the expected benefits of active cooperation by PSEs and active participation by community residents, thereby accelerating the system's evolution toward collaborative governance. However, excessive incentives increase the cost burden of guided cooperation for grassroots governments and weaken the sustainability of co-production. This indicates that incentive mechanisms should not simply pursue higher subsidy levels. Instead, they should remain moderate, precise, and sustainable so that they can activate the participation of social actors without

creating excessive fiscal or administrative pressure for grassroots governments. Fourth, government incentives and social capital exhibit a complementary relationship. Social capital can reduce communication, coordination, and transaction costs among multiple actors through trust, norms, and interaction networks, thereby partially substituting for external incentives. Fifth, social capital has a constraining effect on opportunistic benefits. Social capital can inhibit actors from pursuing opportunistic benefits by reducing cooperation costs, strengthening interactive supervision, and enhancing a sense of shared responsibility. In this way, social capital facilitates the transformation of co-production from externally driven cooperation to internally sustained stability.

6.2. Policy Implication

First, grassroots governments should shift their role from direct administrative providers of community safety services to organizers and facilitators of cooperative conditions. During the initiation of cooperation, they can establish deliberative platforms to clarify the respective roles and responsibilities of grassroots governments, PSEs, and community residents, and develop regular mechanisms for deliberation, task allocation, risk reporting, and coordinated response, thereby promoting more stable multi-actor co-operation. Second, moderate, targeted, and sustainable incentive mechanisms should be established. Incentives for PSEs can be linked to verifiable performance outcomes, such as safety inspections, hazard reporting, facility maintenance, and emergency coordination. For community residents, participation benefits can be enhanced through point-based incentives, recognition incentives, and certification of volunteer services. Meanwhile, the effectiveness of incentive mechanisms should be regularly evaluated, with reasonable cost ceilings and dynamic exit mechanisms established to prevent community safety co-production from becoming excessively dependent on high-intensity fiscal investment. Third, information disclosure and accountability tracking mechanisms should be strengthened. Since sanction mechanisms can only become effective constraints when formalistic responses, passive participation, and opportunistic behaviors can be identified in a timely manner, a whole-process recording mechanism should be established to cover task allocation, hazard reporting, response progress, and handling outcomes. In addition, the identifiability of governance behaviors should be enhanced through appropriate information disclosure, resident supervision, and regular reporting. Fourth, social capital cultivation should be regarded as an important mechanism for reducing long-term governance costs and constraining opportunistic behaviors. Grassroots governments should enhance trust, norms, and interaction networks among grassroots governments, PSEs, and community residents through repeated interactions, such as deliberative consultation, neighborhood watch programs, emergency drills, and volunteer services. These efforts can reduce the dependence of co-production on intensive external incentives and transform temporary mobilization into routine participation. Fifth, the responsibility boundaries of market actors in community safety governance should be further clarified. Tasks such as security patrols, facility maintenance, risk reporting, and emergency coordination should be incorporated into community governance evaluation systems. At the same time, training, joint prevention and control, and information sharing should be strengthened to enhance the capacity of PSEs to participate in community safety governance. These measures can encourage market actors to move from “formalistic response” toward “active cooperation”.

6.3. Limitations and Future Research

This study has several limitations. First, it mainly focuses on the strategic interactions among three key actors: grassroots governments, PSEs, and community residents. Although this tripartite classification helps explain the complex interactions among the

major participants in community safety co-production, it inevitably overlooks internal heterogeneity within the actors and the potential roles of other participants. For example, in terms of internal heterogeneity, different types of community residents may have different cost–benefit considerations and consequently exhibit diverse behavioral choices. Regarding other participants, additional community organizations may also influence the co-production process. Future research could further refine actor types, incorporate other relevant participants, and introduce heterogeneous payoff parameters into multi-population evolutionary game models to examine how actor heterogeneity and more diverse stakeholder structures affect evolutionary processes and equilibrium conditions. Second, the parameter settings in this study are mainly based on contextual assumptions and theoretical reasoning, and the parameter values have not yet been fully calibrated using authoritative empirical data. For example, the social capital parameter T is a simplified representation based on social capital theory and does not fully capture the multidimensional characteristics of social capital or its differentiated mechanisms of influence. Future research could further decompose the social capital parameter T into dimensions such as trust, norms, networks, and civic participation, and introduce conversion coefficients that reflect differences in actor relationships. This would help examine how different forms of social capital influence strategic evolution and equilibrium conditions through distinct pathways, including costs, benefits, information transparency, and opportunistic benefits. In addition, questionnaire surveys and PSE service evaluation data could be combined to empirically measure parameter values and improve the scientific rigor of parameter calibration. Third, this study selects the PDC practice as the empirical context. However, the single-case study design is constrained by the local governance context and resource conditions, which may limit the applicability of the findings to regions with different socio-cultural backgrounds, particularly those characterized by distinct policy environments and governance traditions. Future research could adopt a multi-case comparative approach, collect parameter data from different regions and governance contexts, and incorporate external factors such as community size, types of property services, and levels of digital governance to further evaluate and improve the validity of the proposed model.

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Abbreviations

The following abbreviations are used in this manuscript:

PSEs	Property Service Enterprises
PDC	Property Deliberation Council
MATLAB	Matrix Laboratory

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