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DRIVING FACTORS ON CORPORATE GREEN INVESTMENTS BEHAVIORS: FROM THE STRATEGIC INTERSECTION OF GOVERNMENTS REGULATION AND PUBLIC PARTICIPATION

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Abstract. As the global community confronts the challenges of climate change, businesses face increasing pressure to adopt sustainable practices. This study develops a tripartite game model to investigate the impact of green investments on corporate performance, considering the dynamic interplay between governments regulations and public participation in shaping strategic initiatives. First, the evolutionary stability strategy (ESS) is identified by solving replicator dynamic equations and performing stability analysis of equilibrium points. Next, the practicability and rationality of the evolutionary game model are assessed by analyzing ESSs under various corporate green investment scenarios. Finally, a case-based example is provided to validate the theoretical findings and support the following arguments: there are eight equilibrium points and four potential ESSs in the game model; the selection of each ESS is primarily determined by the trade-off between costs and revenues for each stakeholder; increased governmental regulatory costs prompt a strategic shift, incentivizing corporations to enhance green investments; while rising penalties drive a preference for green options; and corporations recognizing compensatory responsibilities are steered towards sustainable pathways.

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1. Introduction

Traditionally, corporate management has prioritized short-term economic gains, often neglecting environmental and societal considerations [13]. However, escalating issues such as climate change, resource depletion, and social inequality have heightened the need for corporate social responsibility (CSR) [30, 34]. Green investments, a specific form of CSR, operationalize environmental objectives by allocating financial and non-financial resources to enhance environmental performance. These investments include adopting eco-friendly technologies, improving production processes, enhancing energy efficiency, and promoting green product design [8, 21, 29]. Essentially, corporate green investments aim to mitigate environmental pollution [1, 22]. In practice, however, the motivations for corporate management to engage in green investments include regulatory compliance, estab-

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lishing a green image, and achieving production cost savings [2,41]. This leads to an essential inquiry: do green investments truly contribute to enhanced corporate performance? Moreover, to what extent do the outcomes of these investments align with their original objectives? Addressing these questions is essential for understanding the economic implications of green investments, particularly their efficiency and effectiveness in achieving intended outcomes.

Existing research demonstrates that governments regulation serves as a primary catalyst for corporate environmental actions [46]. The effectiveness of corporate green investments, which reflect the outcomes of environmental practices, is significantly influenced by governments environmental policies. Notably, in China's top-down administrative regulatory system, environmental regulatory authority is distributed between central and local governments. The central government establishes environmental policies and guidelines, while local governments are responsible for their implementation [35]. This decentralization grants local authorities substantial discretion in policy enforcement [15]. Previously, local governments in China, driven by a GDP-focused performance evaluation system, often prioritized short-term economic growth over environmental standards. However, the evolution of ecological and environmental supervision mechanisms has led to a shift in the approach of local governments toward environmental governance. It is noteworthy that corporations, as principal actors in economic activities, predominantly prioritize immediate financial returns, driven by the goal of maximizing profits [10]. In contrast, governments generally emphasize long-term environmental benefits and sustainable societal development [18,25]. This divergence in temporal focus often creates challenges in aligning the objectives of these two entities within the context of green investments initiatives.

As information transparency increases, public demands for corporate environmental responsibility have intensified, compelling companies to address and reduce their environmental impact. As demonstrated by Gu *et al.* [12] and Cao *et al.* [4], public engagement in environmental oversight emerges as an effective long-term stimulus for corporate environmental investments. This approach, representing a form of "soft" regulation, underscores the importance of environmental responsibility in corporate management. Hereafter, Tao *et al.* [31] and Zhang *et al.* [44] explore the influence of public participation on the environmental investments decisions of Chinese companies. The former emphasize that public involvement significantly enhances CSR, reinforcing the notion that public concern for environmental issues can drive social responsibility *via* enhanced market and internal corporate governance mechanisms. The latter focus on public advocacy for environmental rights, noting that increased local environmental regulations resulting from public pressure act as a deterrent against corporate environmental infractions and foster improved environmental performance. Moreover, as service-oriented governments initiatives evolve, governmental responses to public environmental concerns have become more pronounced. However, it is crucial to consider that overly stringent regulations could negatively impact other vital performance indicators, such as regional GDP and tax revenue [26,43].

To comprehensively explore the impact of green investments on corporate performance, it is essential to investigate the strategic intersection of governments regulation and public participation. The interaction between governments entities, corporations, and the public transcends mere policy collaboration [8,23]; it necessitates continuous learning and adaptation to navigate the evolving landscape of environmental responsibility and sustainable business practices [45]. In this complex dynamic, evolutionary game theory offers a valuable analytical framework, providing profound insights into the dynamic strategies employed by decision-makers as they respond to the evolving influences of various stakeholders within the policy landscape. Guided by these considerations, this study aims to address key management questions:

(1) How can the roles and strategic intersection of governments and the public in the decision-making processes related to corporate green investments be thoroughly comprehended and defined?
(2) What strategies are deployed in the interactions among these stakeholders, and how can the dynamic changes in the strategic behaviors of the three pillars be effectively illustrated?
(3) How can the comprehensive cooperation of the tripartite mainstay be promoted to enhance corporate performance through green investments?

To explore these concerns, this study employs a robust tripartite evolutionary modeling approach to examine the intricate decision-making processes of stakeholders involved in corporate green investments, encompassing both governments entities and the general public. Leveraging replicator dynamic equations and stability analysis of equilibrium points, the study presents and simulates the evolutionary stable strategy (ESS) adopted by these stakeholders. Subsequently, the study assesses the practicability and rationality of the evolutionary game model by analyzing ESSs corresponding to various scenarios. Finally, SF Holding Co., Ltd. (henceforth referred to as SF Express), a prominent player in China's express delivery industry, is chosen as a case study to empirically validate the efficacy of the game-theoretic modeling.

In fulfilling such plans of attack, this study provides noteworthy contributions in the following ways. First, diverging from prior studies that predominantly treat governments regulation as an external factor with a unidirectional impact on corporate green investments, this study undertakes a detailed examination of the interplay between governments regulation and market mechanisms. By integrating considerations of public behavior into corporate strategic planning, it highlights the interconnected influence among diverse stakeholders.

Second, recognizing the bounded rationality of multiple stakeholders, it acknowledges that time is needed for them to adjust their strategies. The tripartite evolutionary game model provides intriguing insights beyond those offered by conventional corporate green investment concepts. This model, which better reflects real-world dynamics than a static game model, analyzes the impact of governments actions and public feedback on corporate green investments strategies from a dynamic and long-term perspective.

Third, by focusing on a prominent player in China's express delivery industry as a case study, this study not only sheds light on the sufficient overall conditions for the tripartite game to converge to the ideal state, it also reveals the influence of varying stakeholder levels on the enhancement of corporate performance.

2. Methodology

2.1. Construction of the evolutionary game model

Corporate green investments are intricately linked to the interplay among diverse stakeholders with varying decision-making capacities, attributed to their distinct positions and benefit requirements. To address this complexity, this study proposes a dynamic evolutionary game model of corporate green investments decision involving governments, corporations, and the general public. Over successive game iterations, stakeholders strategically deploy tactics to counteract each other's strategies, actively seeking the optimal approach to achieve a dynamic equilibrium.

Environmental monitoring has emerged as a crucial function for service-oriented governments agencies [20]. Rigorous oversight of industrial environmental practices by governmental bodies does not directly translate to an enhanced reputation. Alternatively, lax monitoring may incur the risk of public dissatisfaction and negative sentiment, further undermining trust in the governments [39]. Consequently, governments are confronted with two strategic options, *i.e.*, {strict regulation, passive regulation}. If the proportion of governments choosing the "strict regulation" strategy is represented as x, then the proportion choosing "passive regulation" is $1 - x$.

The drive for economic maximization continues to be the primary motivator for production and operations, often leading businesses to forgo green investments without regulatory mandates [3]. Governmental interventions, through a spectrum of incentives and penalties linked to a company's emissions, significantly shape the decision to make environmental investments [14, 44]. This creates a dichotomy in strategic choices for corporations, namely, {green investments, traditional investments}, with the respective proportions denoted as y and $1 - y$, respectively.

Effective pollution control necessitates robust public engagement, which empowers stakeholders to articulate their concerns, share knowledge, and engage in discourse regarding the environmental implications [5]. As demonstrated by Yang [40], active citizen participation can yield substantial economic advantages by reducing the expenses associated with governments environmental oversight. Nonetheless, the tactics employed by the public are subject to change, influenced by the measures taken by both governmental bodies and corporations. Consequently, the public's strategic inclination fluctuates between two options, *i.e.*, {participation,

TABLE 1. Parameter symbol descriptions.

Stakeholders	Parameter	Descriptions	Notes
Governments	C_1	Costs of governments' "strict regulation" strategy	$C_1 > 0$
	C_2	Costs of governments' "passive regulation" strategy	$C_2 > 0$
	μ_1	Probability of success of governments' "strict regulation" strategy	$0 < \mu_1 < 1$
	μ_2	Probability of success of governments' "passive regulation" strategy	$0 < \mu_2 < 1$
	W	Benefits for governments' "strict regulation" strategy	$W > 0$
	L	Net loss for governments' "passive regulation" strategy	$L > 0$
Corporations	C_3	Costs of corporate "green investments" strategy	$C_3 > 0$
	C_4	Costs of corporate "traditional investments" strategy	$C_4 > 0$
	R_1	Benefits for corporate "green investments" strategy	$R_1 > 0$
	R_2	Extra benefits for corporate "traditional investments" strategy	$R_2 > 0$
	S_1	Subsidies for corporate "green investments" strategy	$S_1 > 0$
	P	Penalties for corporate "traditional investments" strategy	$P > 0$
Public	C_5	Costs of general public's "participation" strategy	$C_5 > 0$
	R_3	Benefits for public's "participation" strategy	$R_3 > 0$
	S_2	Compensations for general public's losses	$S_2 > 0$

non-participation}. The proportion of the "participation" strategy is denoted as z, while the complementary "non-participation" strategy is represented as $1 - z$.

In the tripartite evolutionary model, the following assumptions are adopted. When governments pursue a strategy of "strict regulation", the associated costs are denoted by C_1; while the total social and environmental benefits, including enhanced governments credibility, public satisfaction, and improved regional environmental quality, are represented by W. In contrast, when governments opt for a strategy of "passive regulation", the supervisory incentives provided to the general public are denoted by C_2. Under "passive regulation", governments rely on public reports and evidence of corporate failures in green investments. Consequently, the probability of success μ_2 for "passive regulation" is higher than that for "strict regulation" μ_1, ultimately satisfying the criteria of $0 < \mu_1 < \mu_2 < 1$.

If corporations choose the "green investments" strategy, the incurred costs are denoted by C_3. In this case, corporations can receive an economic subsidy S_1 from the governments and reap additional benefits R_1, such as improved corporate reputation and an increase in potential customers. Conversely, if corporations continue with the "traditional investments" strategy, the associated costs are represented by C_4, with $C_4 < C_3$. Concurrently, corporations gain other advantages R_2, including reduced implementation costs for corporate strategies, an appreciation in property value, and increased investor interest. It is important to note that corporations pursuing traditional investments will face administrative penalties P. Additionally, subsidies S_2 are provided to the public to compensate for losses, including the impact of emissions from corporate manufacturing and operations on affordable production and living resources.

When the general public supervises corporate evasion of green investments, the cost of the "participation" strategy is denoted by C_5. The public then gains a positive income R_3 as a side benefit of their participation. However, if corporations fail to implement "green investments" and the governments adopt a "passive regulation" strategy, the public incurs a net loss L, which includes losses related to life, health, and labor force. Based on the model's underlying assumptions, the primary factors considered by the governments, corporations, and the general public in formulating their respective strategies are evaluated. The specifications for each parameter are listed in Table 1, and the relationships among the three stakeholders are depicted in Figure 1.

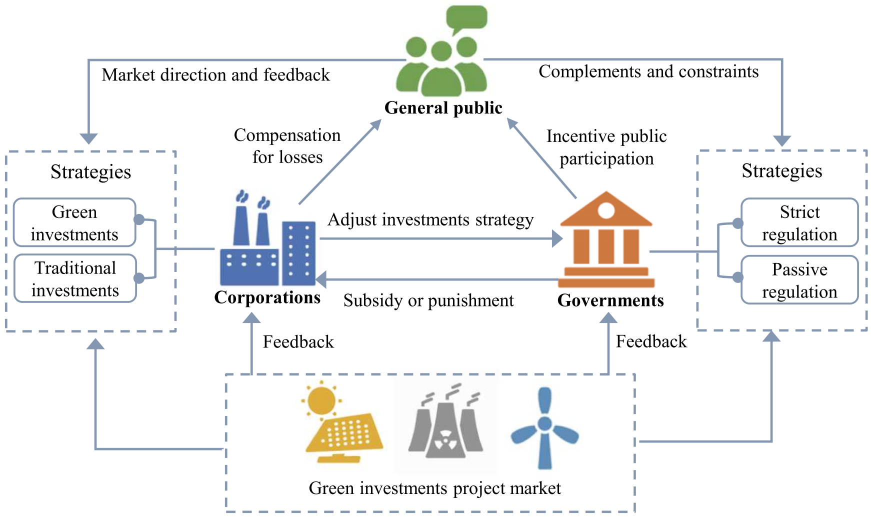

FIGURE 1. Stakeholders' relationships in the green investments.

2.2. Payoffs of stakeholders

2.2.1. Scenario with the general public's participation strategy

The governments' expected payoffs. Under the premise of the general public's "participation" strategy, the expected payoff of the governments with "strict regulation" strategy is $-C_1 - S_1$; however, this expected payoff would change to $\mu_1(W+P)-C_1+\mu_2 W$ if corporations do not adhere to the "green investments" strategy. In contrast, the excepted payoff of the governments with the "passive regulation" strategy equals $-C_2-S_1$; and more in specific, once the corporate side persists in the "traditional investments" strategy, the governments' expected payoff then alters to $\mu_2(W+P)-C_2$.

The corporate expected payoffs. With public participation, regardless of the governments' strategy, the expected payoff for corporations adopting the "green investments" strategy is $R_1-C_3+S_1$. Once the "traditional investments" strategy becomes the optimal choice for the corporations, their expected payoff would change to $(1-\mu_1)R_2-\mu_1(P+C_4+S_2)$, accompanied by governments actively supervision; but it then alters to $(1-\mu_2)R_2-\mu_2(P+C_4+S_2)$ if both governments and corporations are passive.

The public's expected payoffs. When both the governments and corporations seriously fulfill their responsibilities, *i.e.*, the strategies of "strict regulation" and "green investments" are preferred, the expected payoff for the general public equals R_3; but the expected payoff then alters to $\mu_2 S_2 + R_3 + C_2 - C_5 - L$ when both parties shirk their responsibilities, Moreover, once the governments' side persevere in "passive regulation", the expected payoff for the general public turns to $R_3 + C_2 - L$; while when corporate side suspends the "green investments", the expected payoff now becomes $\mu_1 S_2 + R_3 - C_5$.

Based on the foregoing analysis, the expected payoff of stakeholders with the general public's strategy of "participation" strategy are summarized in Table 2.

2.2.2. Scenario without the public's participation strategy

The governments' expected payoffs. In the absence of public "participation", if both the governments and corporations perform their duties conscientiously, the governments' expected payoff is $-C_1-S_1$; once the corporations side unilaterally refuses to make "green investments", this payoff changes to $\mu_1(W+P)-C_1$.

TABLE 2. Expected payoff of stakeholders with the general public's participation (z).

Governments	Corporations	
	Green investments (y)	Traditional investments ($1-y$)
Strict regulation (x)	$-C_1 - S_1$ $R_1 - C_3 + S_1$ R_3	$\mu_1 (W+P) - C_1 + \mu_2 W$ $(1-\mu_1)R_2 - \mu_1 (P + C_4 + S_2)$ $\mu_1 S_2 + R_3 - C_5$
Passive regulation ($1-x$)	$-C_2 - S_1$ $R_1 - C_3 + S_1$ $R_3 + C_2 - L$	$\mu_2 (W+P) - C_2$ $(1-\mu_2)R_2 - \mu_2 (P + C_4 + S_2)$ $\mu_2 S_2 + R_3 + C_2 - C_5 - L$

TABLE 3. Expected payoff of stakeholders without the general public's participation ($1-z$).

Governments	Corporations	
	Green investments (y)	Traditional investments ($1-y$)
Strict regulation (x)	$-C_1 - S_1$ $R_1 - C_3 + S_1$ 0	$\mu_1 (W+P) - C_1$ $(1-\mu_1)R_2 - \mu_1 (P + C_4 + S_2)$ $\mu_1 S_2$
Passive regulation ($1-x$)	$-C_2$ $R_1 - C_3$ $-L$	0 $R_2 - C_4 - S_2$ $S_2 - L$

When the governments select the "passive regulation" as the strategic premise, the expected payoff equals $-C_2$; but it becomes zero if both the governments and corporations act self-interestedly.

The corporate expected payoffs. Under the scenario of "non-participation" by the public and "passive regulation" by the governments, the expected payoff for corporations pursuing the "green investments" strategy is $R_1 - C_3$; whereas extra subsidies would achieve when the governments enforce "strict regulation", the payoff for corporations improves to $R_1 - C_3 + S_1$. Conversely, if corporations unilaterally abandon "green investments", their expected payoff is $(1-\mu_1)R_2 - \mu_1(P + C_4 + S_2)$, which changes to $R_2 - C_4 - S_2$ if both governments and corporations neglect their environmental responsibilities.

The general public's expected payoffs. In the occasion that both the governments and corporations perform their respective duties with the "strict regulation" and "green investments" strategies, the expected payoff for the public with the "non-participation" strategy is zero; conversely, if both parties neglect their responsibilities, the public's expected payoff adjusts to $S_2 - L$. Once the governments' side endure in "passive regulation", the general public's expected payoff becomes $-L$; when the corporations unilaterally engage in "traditional investments", the public's expected payoff becomes $\mu_1 S_2$ along with their compensation incomes.

Based on the foregoing analysis, the expected payoff of stakeholders with the general public's strategy of "non-participation" strategy are summarized in Table 3.

2.3. Replicated dynamics equations of tripartite evolutionary game

2.3.1. Replicator dynamic analysis of the governments

For governments, the expected payoffs for choosing "strict regulation" and "passive regulation" are denoted as U_1 and U_2, respectively. According to the Malthusian dynamic equation, if the payoff of a selected strategy exceeds the average payoffs of other strategies, it suggests that this strategy has the potential to outperform

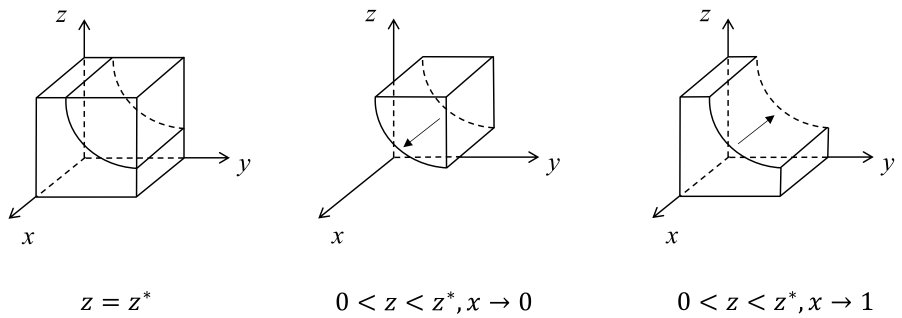

FIGURE 2. Replicator dynamic phase diagram of the government.

alternative strategies and drive the evolution of the group [11]. This indicates the strategy's ability to resist mutations and promote effective adaptation within the evolutionary process. Consequently, the replicator dynamics equation for governments is (see further details in Appendix A.1):

$$\begin{aligned} F(x) = \frac{\mathrm{d}x}{\mathrm{d}t} &= x(1-x)(U_1 - U_2) = x\,(1-x)\left\{yz\,(\mu_2 P - C_1 + S_1)\right. \\ &\left.+ y\left[C_2 - \mu_1\,(W+P) - S_1\right] + z\,(C_2 - \mu_2 P) + \mu_1\,(W+P) - C_1\right\}. \end{aligned} \tag{1}$$

The derivative of the governments' replicator dynamics equation is given by:

$$\begin{aligned} F^{'}(x) = \frac{\mathrm{d}F(x)}{\mathrm{d}t} &= (1-2x)\left\{yz\,(\mu_2 P - C_1 + S_1)\right. \\ &\left.+ y[C_2 - \mu_1(W+P) - S_1] + z\,(C_2 - \mu_2 P) + \mu_1\,(W+P) - C_1\right\}. \end{aligned} \tag{2}$$

If $z = z^* = \frac{C_1 - \mu_1(W+P) - y[C_2 - \mu_1(W+P) - S_1]}{y(\mu_2 P - C_1 + S_1) - \mu_2 P + C_2}$, $F(x) = 0$, indicating that all game strategies are in a steady state. However, if $z \neq z^*$, assuming $F(x) = 0$, then $x = 0$ and $x = 1$ are two stable points (see further details in Appendix B.1). Based on this equation, two distinct states are analyzed, as illustrated in the dynamic phase diagram presented in Figure 2. This analysis leads to the following propositions.

Proposition 1. *The probability of governments adopting the "strict regulation" strategy is directly correlated with scenarios where corporations pursue a "traditional investments" strategy and the general public remains uninvolved. In such instances, a strict regulatory policy is often the governments' response.*

Proposition 2. *The governments tend to favor a more "passive regulation" strategy when the costs of stringent regulation exceed its revenue. Consequently, there is an inverse relationship between the probability of the governments choosing "strict regulation" and the associated costs of implementing such regulation.*

2.3.2. Replicator dynamic analysis of the corporations

For corporations, the expected payoffs for choosing the strategies of "green investments" and "traditional investments" are denoted as U_3 and U_4, respectively. The replicator dynamics equation for corporations is given by (see further details in Appendix A.2):

$$\begin{aligned} F\,(y) = \frac{\mathrm{d}y}{\mathrm{d}t} &= y\,(1-y)\,(U_3 - U_4) = y\,(1-y)\left\{-xz\left[\mu_2\,(R_2 + P + C_4 + S_2)\right.\right. \\ &+ S_1 - C_4 - S_2] + x\left[\mu_1\,(R_2 + P + C_4 + S_2) + S_1 - C_4 - S_2\right] \\ &\left.+ z\left[\mu_2\,(R_2 + P + C_4 + S_2) + S_1 - C_4 - S_2\right] + R_1 - C_3 + S_2 - R_2 + C_4\right\}. \end{aligned} \tag{3}$$

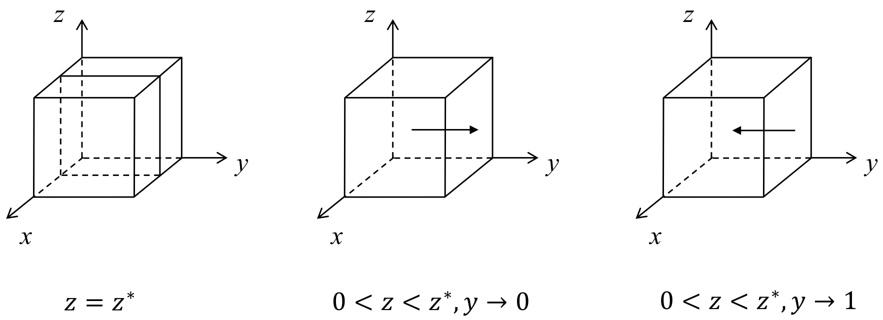

FIGURE 3. Replicator dynamic phase diagram of the corporations.

The derivation of the replicator dynamics equation for corporations is as follows:

$$\begin{aligned} F'(y) = \frac{\mathrm{d}F(y)}{\mathrm{d}t} &= (1-2y)\{-xz[\mu_2(R_2+P+C_4+S_2)+S_1-C_4-S_2] \\ &+ x[\mu_1(R_2+P+C_4+S_2)+S_1-C_4-S_2] + z[\mu_2(R_2+P+C_4+S_2) \\ &+ S_1-C_4-S_2] + (R_1-C_3+S_2-R_2+C_4)\}. \end{aligned} \tag{4}$$

If $z = z^* = \frac{-x[\mu_1(R_2+P+C_4+S_2)+S_1-C_4-S_2]-R_1+C_3-S_2+R_2-C_4}{(1-x)[\mu_2(R_2+P+C_4+S_2)+S_1-C_4-S_2]}$, $F(y) = 0$, indicating that all game strategies are in a steady state. If $z \neq z^*$, assuming $F(y) = 0$, then $y = 0$ and $y = 1$ are two stable points (see further details in Appendix B.2). According to the preceding equation, two distinct states are explored, and the corresponding dynamic phase diagram is depicted in Figure 3. The preceding analysis leads to the following propositions.

Proposition 3. *Corporations are inclined to adopt the "green investments" strategy when confronted with both stringent governments regulation and active public involvement. The probability of corporations implementing such a strategy correlates positively with the intensity of governments regulation and the level of public engagement.*

Proposition 4. *Corporations demonstrate reluctance in implementing the "green investments" strategy when the associated costs outweigh the returns. There is a negative correlation between the feasibility of adopting the "green investments" strategy and their execution costs; as the latter increases, the probability of corporations choosing these strategies decreases.*

2.3.3. Replicator dynamic analysis of the general public

For the general public, the expected payoffs for choosing the strategies of the "participation" and "non-participation" are denoted as U_5 and U_6 respectively. The replicator dynamics equation for the public is (see further details in Appendix A.3):

$$\begin{aligned} F(z) = \frac{\mathrm{d}z}{\mathrm{d}t} &= z(1-z)(U_5-U_6) = z(1-z)\{xy\mu_2S_2 + x[(1-\mu_2)S_2-C_2] \\ &+ y[(1-\mu_2)S_2+C_5] + R_3 + \mu_2S_2 + C_2 - C_5 - S_2\}. \end{aligned} \tag{5}$$

The derivative of the public's replicator dynamics equation is as follows:

$$\begin{aligned} F'(z) = \frac{\mathrm{d}F(z)}{\mathrm{d}t} &= (1-2z)\{xy\mu_2S_2 + x[(1-\mu_2)S_2-C_2] + y[(1-\mu_2)S_2+C_5] + R_3 + \mu_2S_2 \\ &+ C_2 - C_5 - S_2\}. \end{aligned} \tag{6}$$

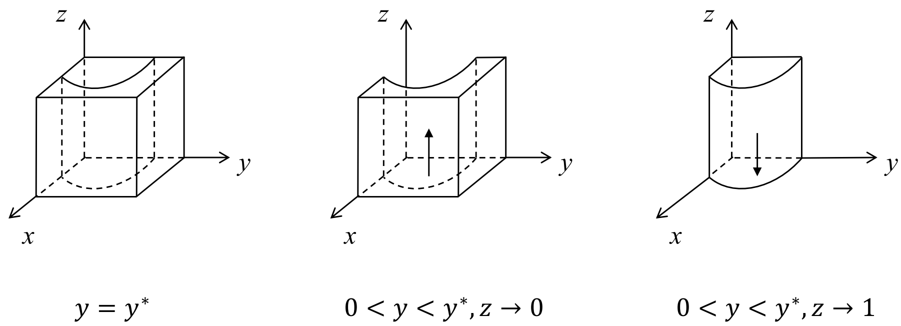

FIGURE 4. Replicator dynamic phase diagram of the public.

If $y = y^* = \frac{x[C_2-(1-\mu_2)S_2]-R_3-\mu_2 S_2-C_2+C_5+S_2}{\mu_2 S_2(x-1)+S_2+C_5}$, $F(z) = 0$, indicating that all game strategies are in a steady state. If $y \neq y^*$, assuming $F(z) = 0$, then $z = 0$ and $z = 1$ are two stable points (see further details in Appendix B.3). According to this equation, two distinct states are analyzed, with the corresponding dynamic phase diagram illustrated in Figure 4. The preceding analysis leads to the following propositions.

Proposition 5. *Public "participation" strategy is more probable when the benefits outweigh the costs of involvement. Consequently, there is typically an inverse relationship between the cost of participation and the probability of public engagement in these strategies.*

Proposition 6. *The probability of the public adopting a "participation" strategy rises when there are significant benefits to be gained from corporate "green investments" and stringent governments regulations. Essentially, the potential for higher gains positively influences public decisions to participate.*

3. Evolutionary stable analysis

3.1. Equilibrium solution

The previous replicator dynamics analysis indicates that the probabilities of adopting strategies by the central regulator, corporations, and the general public are time-dependent, denoted as $x(t), y(t), z(t)$, respectively, where $x(t), y(t), z(t) \in (0, 1)$. These probabilities evolve according to the following equation:

$$\begin{cases} F(x) = x(1-x)\{yz(\mu_2 P - C_1 + S_1) + y[C_2 - \mu_1(W+P) - S_1] \\ \qquad +z(C_2 - \mu_2 P) + \mu_1(W+P) - C_1\} = 0 \\ F(y) = y(1-y)\left\{\begin{matrix} -xz[\mu_2(R_2+P+C_4+S_2) + S_1 - C_4 - S_2] + x\begin{bmatrix}\mu_1(R_2+P+C_4+S_2) \\ +S_1 - C_4 - S_2\end{bmatrix} \\ +z[\mu_2(R_2+P+C_4+S_2) + S_1 - C_4 - S_2] + R_1 - C_3 + S_2 - R_2 + C_4 \end{matrix}\right\} = 0 \\ F(z) = z(1-z)\{xy\mu_2 S_2 + x[(1-\mu_2)S_2 - C_2] + y[(1-\mu_2)S_2 + C_5] + R_3 + \mu_2 S_2 + C_2 - C_5 - S_2\} = 0. \end{cases} \tag{7}$$

Based on equation (7), there are eight distinctive equilibrium points, *i.e.*, $E_1(0,0,0), E_2(0,0,1), E_3(0,1,0), E_4(0,1,1), E_5(1,0,0), E_6(1,0,1), E_7(1,1,0), E_8(1,1,1)$. At each of these equilibrium points, stakeholders adopt pure strategies, which define the domain boundary

$\Omega = \{x, y, z\,|0 < x, y, z < 1\}$. Additionally, there may be hybrid equilibrium points, denoted as E_9, within Ω:

$$\begin{cases} x(1-x)\left\{yz\left(\mu_2 P - C_1 + S_1\right) + y\left[C_2 - \mu_1(W+P) - S_1\right] + z\left(C_2 - \mu_2 P\right) + \mu_1(W+P) - C_1\right\} = 0 \\ y(1-y)\left\{\begin{matrix} -xz\left[\mu_2\left(R_2 + P + C_4 + S_2\right) + S_1 - C_4 - S_2\right] \\ +x\left[\mu_1\left(R_2 + P + C_4 + S_2\right) + S_1 - C_4 - S_2\right] \\ +z\left[\mu_2\left(R_2 + P + C_4 + S_2\right) + S_1 - C_4 - S_2\right] + R_1 - C_3 + S_2 - R_2 + C_4 \end{matrix}\right\} = 0 \\ z(1-z)\left\{xy\mu_2 S_2 + x\left[\left(1-\mu_2\right)S_2 - C_2\right] + y\left[\left(1-\mu_2\right)S_2 + C_5\right] + R_3 + \mu_2 S_2 + C_2 - C_5 - S_2\right\} = 0. \end{cases} \tag{8}$$

However, if E_9 does not coincide with Ω (*i.e.*, $E_9 \neq \Omega$), it should be excluded from consideration.

3.2. Asymptotic stability

The equilibrium points identified from the replicator dynamics equation provide an initial understanding of the evolutionary stability but are not sufficient to precisely determine the ESS. To this end, according to Selten [28] and Weibull [38], a pure-strategy Nash equilibrium is considered asymptotically stable in the context of a multi-party evolutionary game. In such cases, the asymptotically stable equilibrium point, or "sink", must be an ESS within the game framework. Thus, if an equilibrium point in the tripartite evolutionary game is found to be asymptotically stable, it will be a pure-strategy Nash equilibrium. Notably, E_9, which represents a hybrid strategy, does not qualify as a "sink" and should not be considered in this analysis. To assess the asymptotic stability of the pure-strategy equilibria, based on Friedman [11], the following constitutes the game's Jacobian matrix:

$$J = \begin{bmatrix} (1-2x)\begin{pmatrix} yz\left(\mu_2 P - C_1 + S_1\right) \\ +y\left[C_2 - \mu_1(W+P) - S_1\right] \\ +z\left(C_2 - \mu_2 P\right) \\ +\mu_1(W+P) - C_1 \end{pmatrix} & x(1-x)\begin{pmatrix} z\left(\mu_2 P - C_1 + S_1\right) \\ +\left[C_2 - \mu_1(W+P) - S_1\right] \end{pmatrix} & x(1-x)\begin{pmatrix} y\left(\mu_2 P - C_1 + S_1\right) \\ +\left(C_2 - \mu_2 P\right) \end{pmatrix} \\ y(1-y)\begin{pmatrix} -z\begin{bmatrix} \mu_2\left(R_2 + P + C_4 + S_2\right) \\ +S_1 - C_4 - S_2 \end{bmatrix} \\ +\begin{bmatrix} \mu_1\left(R_2 + P + C_4 + S_2\right) \\ +S_1 - C_4 - S_2 \end{bmatrix} \end{pmatrix} & (1-2y)\begin{pmatrix} -xz\begin{bmatrix} \mu_2\left(R_2 + P + C_4 + S_2\right) \\ +S_1 - C_4 - S_2 \end{bmatrix} \\ +x\left[\mu_1\left(R_2 + P + C_4 + S_2\right) + S_1 - C_4 - S_2\right] \\ +z\left[\mu_2\left(R_2 + P + C_4 + S_2\right) + S_1 - C_4 - S_2\right] \\ +\left(R_1 - C_3 + S_2 - R_2 + C_4\right) \end{pmatrix} & y(1-y)\left((1-x)\begin{bmatrix} \mu_2\left(R_2 + P + C_4 + S_2\right) \\ +S_1 - C_4 - S_2 \end{bmatrix}\right) \\ z(1-z)\begin{pmatrix} y\mu_2 S_2 \\ +\left(1-\mu_2\right)S_2 - C_2 \end{pmatrix} & z(1-z)\begin{pmatrix} x\mu_2 S_2 \\ +\left[\left(1-\mu_2\right)S_2 + C_5\right] \end{pmatrix} & (1-2z)\begin{pmatrix} (1+xy)\mu_2 S_2 \\ +(x+y)\left[\left(1-\mu_2\right)S_2 - C_2\right] \\ +R_3 + C_2 - C_5 - S_2 \end{pmatrix} \end{bmatrix}. \tag{9}$$

Then, the Jacobian matrix of the tripartite evolutionary game at $E_1(0,0,0)$ is giving:

$$J_1 = \begin{bmatrix} \mu_1\left(W+P\right) - C_1 & 0 & 0 \\ 0 & R_1 + S_2 + C_4 - C_3 - R_2 & 0 \\ 0 & 0 & R_3 + (1-\mu_2)S_2 + C_2 - C_5 \end{bmatrix}. \tag{10}$$

The eigenvalues of matrix J_1 are given by: $\lambda_1 = \mu_1\left(W+P\right) - C_1$, $\lambda_2 = R_1 + S_2 + C_4 - C_3 - R_2$ and $\lambda_3 = R_3 + (1-\mu_2)S_2 + C_2 - C_5$. By observing λ_1, it is evident that $\mu_1\left(W+P\right)$ represents the total benefits derived from effective governments regulation and penalty enforcement, while C_1 the regulatory costs, including resources, time, and other inputs required for the implementation and enforcement of these regulations. For regulation to be deemed effective, the benefits must exceed or at least cover the associated costs. If $\mu_1\left(W+P\right) < C_1$, the regulation may be considered an inefficient allocation of resources from an economic perspective. According to the asymptotic approach of Lyapunov [24], an equilibrium point is asymptotically stable only if all eigenvalues are negative. Consequently, $E_1\left(0,0,0\right)$ is not asymptotically stable. Similarly, the eigenvalues of equilibrium points $E_2 - E_8$ can suggest asymptotic stability, contingent upon meeting their respective criteria, as summarized in Table 4. By observing Table 4, it can be found that the Jacobian matrices for equilibrium points $E_3\left(0,1,0\right)$, $E_5\left(1,0,0\right)$, $E_7\left(1,1,0\right)$ and $E_8(1,1,1)$ each possess at least one positive eigenvalue, signifying the existence of a saddle point. Therefore, these equilibrium points do not achieve asymptotic stability.

Based on the above analysis of asymptotic stability, four equilibrium points $E_2\left(0,0,1\right)$, $E_4\left(0,1,1\right)$, $E_6\left(1,0,1\right)$ and $E_8(1,1,1)$, may become potential sinks, as detailed in Table 5.

TABLE 4. Eigenvalues of equilibrium points.

Equilibrium point	Eigenvalues		
	λ_1	λ_2	λ_3
$E_1\,(0,0,0)$	$\mu_1\,(W+P)-C_1$	$R_1+S_2+C_4-C_3-R_2$	$R_3+(1-\mu_2)S_2+C_2-C_5$
$E_2\,(0,0,1)$	$\mu_1\,(W+P)+C_2-\mu_2 P-C_1$	$\mu_2\,(R_2+P+C_4+S_2)$ $+R_1+S_1-C_3-R_2$	$-R_3+(1-\mu_2)S_2-C_2+C_5$
$E_3\,(0,1,0)$	$C_2-S_1-C_1$	$C_3-R_1-S_2+R_2-C_4$	R_3-C_5
$E_4\,(0,1,1)$	$2C_2-2C_1$	$-\mu_2\,(R_2+P+C_4+S_2)$ $-R_1-S_1+C_3+R_2$	C_5-R_3
$E_5\,(1,0,0)$	$-\mu_1\,(W+P)+C_1$	$\mu_1\,(R_2+P+C_4+S_2)$ $+R_1+S_1-C_3-R_2$	R_3-C_5
$E_6\,(1,0,1)$	$-C_2+\mu_2 P$ $-\mu_1\,(W+P)+C_1$	$\mu_1\,(R_2+P+C_4+S_2)$ $+R_1+S_1-C_3-R_2$	C_5-R_3
$E_7\,(1,1,0)$	$-C_2+S_1+C_1$	$-\mu_1\,(R_2+P+C_4+S_2)$ $-R_1-S_1+C_3+R_2$	$S_2-C_2+R_3-C_5$
$E_8\,(1,1,1)$	$2C_1-2C_2$	$-\mu_1\,(R_2+P+C_4+S_2)$ $-R_1-S_1+C_3+R_2$	$-S_2+C_2-R_3+C_5$

TABLE 5. Conditions of stability at equilibrium point.

Equilibrium point	Conditions of ESS
$E_2\,(0,0,1)$	$\mu_1\,(W+P)+C_2-\mu_2 P-C_1<0$
	$\mu_2\,(R_2+P+C_4+S_2)+R_1+S_1-C_3-R_2<0$
$E_4(0,1,1)$	$C_2-C_1<0$
	$\mu_2\,(R_2+P+C_4+S_2)+R_1+S_1-C_3-R_2>0$
$E_6\,(1,0,1)$	$\mu_1\,(W+P)+C_2-\mu_2 P-C_1>0$
	$\mu_1\,(R_2+P+C_4+S_2)+R_1+S_1-C_3-R_2<0$
$E_8\,(1,1,1)$	$C_1-C_2<0$
	$\mu_1\,(R_2+P+C_4+S_2)+R_1+S_1-C_3-R_2>0$

4. Results

4.1. Simulation design

Although the game-theoretic models presented in this study are inherently analytical, the objective is to integrate realistic scenarios to visually represent convergence patterns among multiple stakeholders and illustrate the impact of key parameter values on the ESS. To effectively simulate the tripartite evolutionary game model, equations (1), (3), and (5) can be discretized to facilitate the tracking of an asymptotically stable trajectory. To this end, the time interval may thus be set to Δt. At each interval, all stakeholders – governments, corporations, and the general public – make strategic decisions, gaining proportionate benefits from each game round.

Subsequently, participants iterate by adjusting their strategies based on the outcomes of the preceding interval. This iterative process transforms the tripartite dynamic replication system into a discretized form:

$$\begin{cases} \frac{\mathrm{d}x}{\mathrm{d}t} \approx \frac{x(t+\Delta t)-x(t)}{\Delta t} = x(1-x)\left\{\begin{array}{l} yz(\mu_2 P - C_1 + S_1) + y[C_2 - \mu_1(W+P) - S_1] + z(C_2 - \mu_2 P) \\ +\mu_1(W+P) - C_1 \end{array}\right\} \\ \frac{\mathrm{d}y}{\mathrm{d}t} \approx \frac{y(t+\Delta t)-y(t)}{\Delta t} = y(1-y)\left\{\begin{array}{l} -xz[\mu_2(R_2+P+C_4+S_2)+S_1-C_4-S_2] + x\begin{bmatrix} \mu_1(R_2+P+C_4+S_2) \\ +S_1-C_4-S_2 \end{bmatrix} \\ +z[\mu_2(R_2+P+C_4+S_2)+S_1-C_4-S_2] + R_1 - C_3 + S_2 - R_2 + C_4 \end{array}\right\} \\ \frac{\mathrm{d}z}{\mathrm{d}t} \approx \frac{z(t+\Delta t)-z(t)}{\Delta t} = z(1-z)\left\{\begin{array}{l} xy\mu_2 S_2 + x[(1-\mu_2)S_2 - C_2] + y[(1-\mu_2)S_2 + C_5] + R_3 \\ +\mu_2 S_2 + C_2 - C_5 - S_2 \end{array}\right\}. \end{cases} \tag{11}$$

Suppose the time interval $\Delta t = 1$, hereafter:

$$\begin{cases} x(t+1) = x(t)[2-x(t)]\left\{\begin{array}{l} y(t)z(t)(\mu_2 P - C_1 + S_1) + y[C_2 - \mu_1(W+P) - S_1] + z(t)(C_2 - \mu_2 P) \\ +\mu_1(W+P) - C_1 \end{array}\right\} \\ y(t+1) = y(t)[2-y(t)]\left\{\begin{array}{l} -x(t)z(t)[\mu_2(R_2+P+C_4+S_2)+S_1-C_4-S_2] + x(t)\begin{bmatrix} \mu_1(R_2+P+C_4+S_2) \\ +S_1-C_4-S_2 \end{bmatrix} \\ +z(t)[\mu_2(R_2+P+C_4+S_2)+S_1-C_4-S_2] + R_1 - C_3 + S_2 - R_2 + C_4 \end{array}\right\} \\ z(t+1) = z(t)[2-z(t)]\left\{\begin{array}{l} x(t)y(t)\mu_2 S_2 + x(t)[(1-\mu_2)S_2 - C_2] + y(t)[(1-\mu_2)S_2 + C_5] + R_3 \\ +\mu_2 S_2 + C_2 - C_5 - S_2 \end{array}\right\}. \end{cases} \tag{12}$$

4.2. ESS under different game scenarios

4.2.1. ESS under scenario I

The sink $E_2(0,0,1)$ is the unique ESS when $\mu_1(W+P)+C_2-\mu_2 P-C_1<0$ and $\mu_2(R_2+P+C_4+S_2)+R_1+S_1-C_3-R_2<0$ are met. To satisfy this requirement, in addition to the baseline values, $C_1=2$, $C_2=1$, $C_3=23$, $C_4=2$, $C_5=1$, $\mu_1=0.1$, $\mu_2=0.4$, $R_1=5$, $R_2=10$, $R_3=12$, $W=5$, $S_1=5$, $S_2=2$, $P=20$ are set in Scenario I. The simulation results presented in Figure 5 demonstrate that the choice probabilities for all stakeholders selecting the strategy (x,y,z) steadily increase with each iteration, ultimately converging to $E_2(0,0,1)$. In this equilibrium scenario, when the net revenue for the governments under the "passive regulation" strategy surpasses that under "strict regulation", the former is undeniably preferred. Consequently, the total costs borne by corporations under the governments' "passive regulation" are lower than those associated with the "green investments" strategy. As rational economic agents, corporations prefer to evade the burdens of environmental governance by accepting specific penalties, making "traditional investments" their favored option. Furthermore, the public consistently opts for the "participation" strategy, driven by the pursuit of individual benefits.

4.2.2. ESS under scenario II

The sink $E_4(0,1,1)$ is the unique ESS when $C_2-C_1<0$ and $\mu_2(R_2+P+C_4+S_2)+R_1+S_1-C_3-R_2>0$ are met. To satisfy this requirement, in addition to the baseline values, the following parameters are set for Scenario II, $C_1=10$, $C_2=2$, $C_3=10$, $C_4=6$, $C_5=3$, $\mu_1=0.8$, $\mu_2=0.5$, $R_1=5$, $R_2=1$, $R_3=12$, $W=10$, $S_1=5$, $S_2=5$, $P=13$. As shown in Figure 6, the probability of the strategy x shows a steady downward trend from the initial point, while the probabilities of strategies y and z exhibit steady upward trends, ultimately converging to $E_4(0,1,1)$. In instances where the governments consistently prefer the "passive regulation" approach over "strict regulation" due to lower associated costs, corporations, aiming to avoid fines and compensate the public, are increasingly inclined to adopt proactive "green investments". When the benefits of these investments outweigh the costs, the "participation" strategy becomes the more probable choice for the public. This strategic landscape highlights the dynamic interactions among stakeholders, where considerations of cost and strategic actions intricately shape the system's equilibrium dynamics.

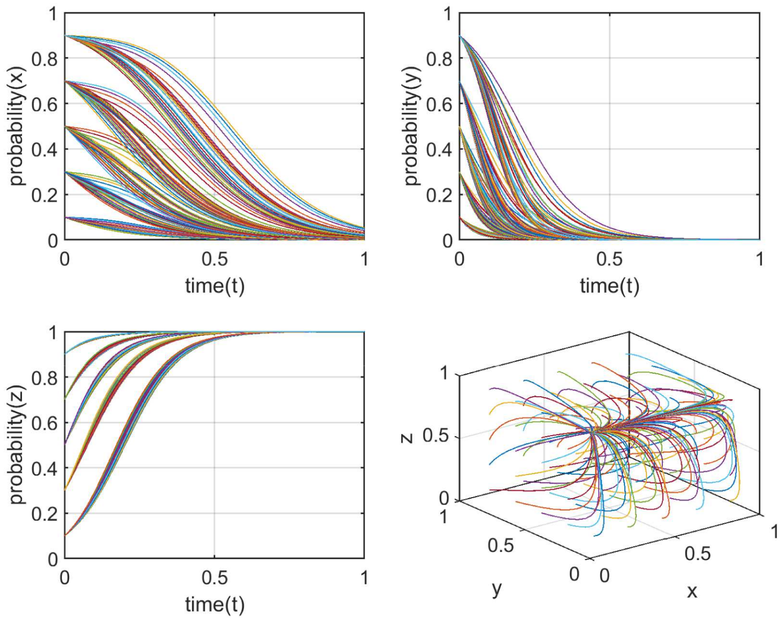

FIGURE 5. The evolution towards the stable equilibrium point $E_2(0,0,1)$.

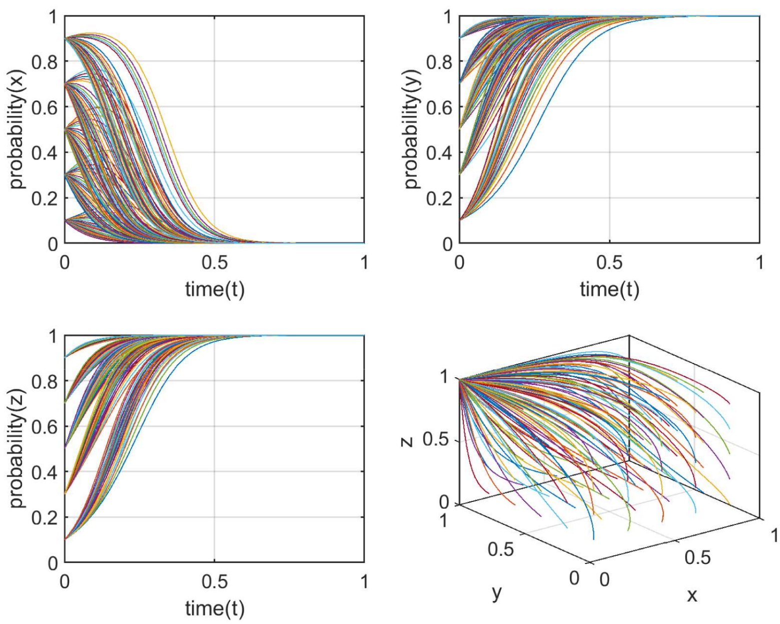

FIGURE 6. The evolution towards the stable equilibrium point $E_4(0,1,1)$.

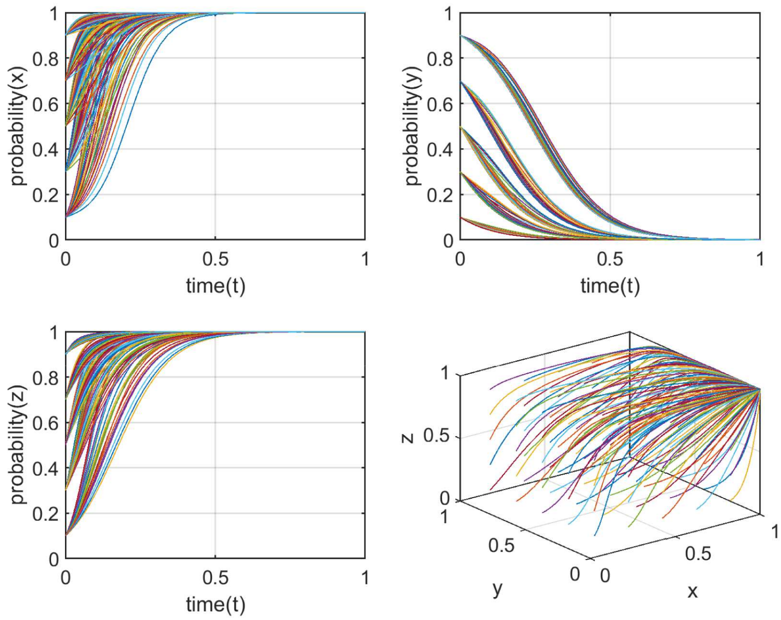

FIGURE 7. The evolution towards the stable equilibrium point $E_6(1, 0, 1)$.

4.2.3. ESS under scenario III

The sink $E_6(1, 0, 1)$ is the unique ESS when $\mu_1(W + P) + C_2 - \mu_2 P - C_1 > 0$ and $\mu_1 (R_2 + P + C_4 + S_2) + R_1 + S_1 - C_3 - R_2 < 0$ are met. To satisfy this requirement, in addition to the baseline values, the following parameters are set for Scenario III $C_1 = 2$, $C_2 = 20$, $C_3 = 12$, $C_4 = 2$, $C_5 = 1$, $\mu_1 = 0.2$, $\mu_2 = 0.4$, $R_1 = 1$, $R_2 = 6$, $R_3 = 12$, $W = 5$, $S_1 = 2$, $S_2 = 5$, $P = 15$. As illustrated in Figure 7, the probabilities for choosing strategies x and z shows an upward trend from the initial state, while the probability of choosing strategy y decreases, ultimately converging to $E_6(1, 0, 1)$. When the costs associated with "passive regulation" exceed those of "strict regulation", the governments generally prefer the latter to protect its interests. Similarly, the public favors the "participation" strategy because the benefits of oversight outweigh the costs of participation. Despite the public's engagement in "participation" and the governments' preference for "strict regulation", corporations, as rational economic agents, resist these measures. This resistance is due to the higher costs associated with corporate green investments compared to the benefits realized.

4.2.4. ESS under scenario IV

The sink $E_8\,(1, 1, 1)$ is the unique ESS when $C_1 - C_2 < 0$ and $\mu_1 (R_2 + P + C_4 + S_2) + R_1 + S_1 - C_3 - R_2 > 0$ are met. To satisfy this requirement, in addition to the baseline values, $C_1 = 3$, $C_2 = 10$, $C_3 = 10$, $C_4 = 2$, $C_5 = 2$, $\mu_1 = 0.5$, $\mu_2 = 0.3$, $R_1 = 15$, $R_2 = 2$, $R_3 = 12$, $W = 5$, $S_1 = 2$, $S_2 = 5$, $P = 15$ are set in Scenario IV. As illustrated in Figure 8, the probabilities for choosing strategies x, y and z show a consistent upward trend, ultimately converging to $E_8\,(1, 1, 1)$. The simulation results reveal that as the costs of "passive regulation" rise and fines for corporations increase, the governments tend to favor "strict regulation" more robustly. In response, corporations are increasingly adopting "green investments", driven by the benefits and potential additional revenue that outweigh the implementation costs. Furthermore, the public's sustained preference for the "participation" strategy aligns with the trends observed in Scenario III, reflecting a consistent inclination towards strategies that offer favorable net benefits.

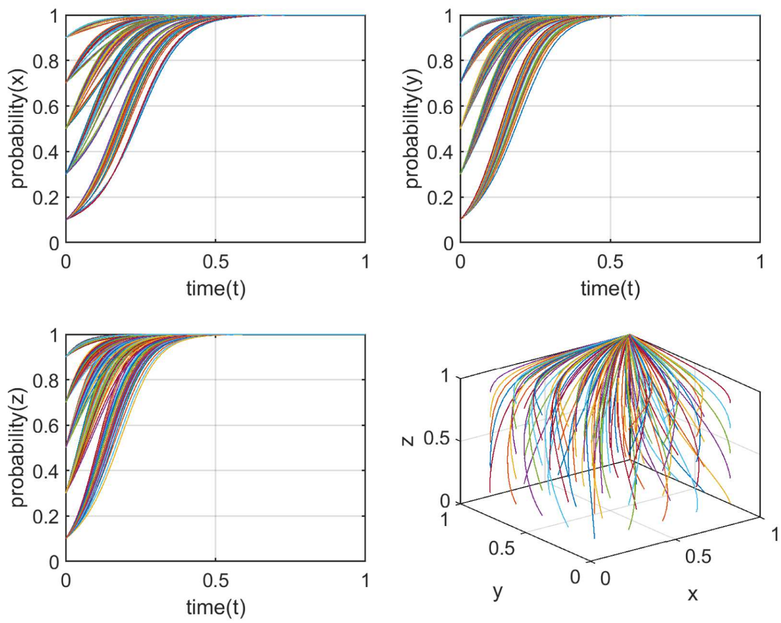

FIGURE 8. The evolution towards the stable equilibrium point $E_8(1, 1, 1)$.

4.3. Sensitivity analysis

The preceding analysis underscores the desirability and feasibility of Scenario III as an optimal outcome for the ESS. To ensure the robustness of these findings, a comprehensive sensitivity analysis is conducted. It involves running simulations where the values of key parameters are systematically varied while keeping other parameters constant. The parameters examined include the cost of governments "passive regulation" (C_2), the penalty imposed by the governments for corporate "traditional investments" (P), and the compensations from corporate for general public's losses (S_2). Numerical simulations are then performed to solve the differential equations governing the ESS dynamics, enabling a precise evaluation of the effects of parameter variations. The initial conditions of the system are set to $x(t_0) = 0.5$, $y(t_0) = 0.5$ and $z(t_0) = 0.5$, representing a balanced starting point for the following analysis.

4.3.1. Effect of the governments' passive regulation costs

To evaluate the impact of governments' "passive regulation" cost (C_2) on system dynamics and strategic choices, the sensitivity analysis involves systematically varying C_2 across low, medium, and high-cost levels, while keeping other parameters constant. As depicted in Figure 9, the analysis reveals a clear preference by the governments for a "passive regulation" strategy when C_2 low, particularly at a minimal value of 1. This inclination reflects a strategic balance between minimizing administrative costs and allowing businesses with a degree of environmental autonomy. However, as C_2 increases, particularly to values of 10 and 20, the strategy shifts toward "strict regulation". This shift is driven by the need to uphold environmental standards, prevent ecological damage, and address rising societal concerns. In the corporate sector, the probability of adopting "green investments" rises sharply with increasing C_2, eventually stabilizing at a higher value of 20. This trend is influenced by various factors, including market strategy, brand image, and the potential costs of non-compliance (*e.g.*, fines and reputational damage). Additionally, the probability of public adaptation increases when C_2 is low, at a value of 1. This suggests that higher associated costs, such as health impacts and environmental risks, may enhance public involvement in oversight and demand accountability from both businesses and the governments.

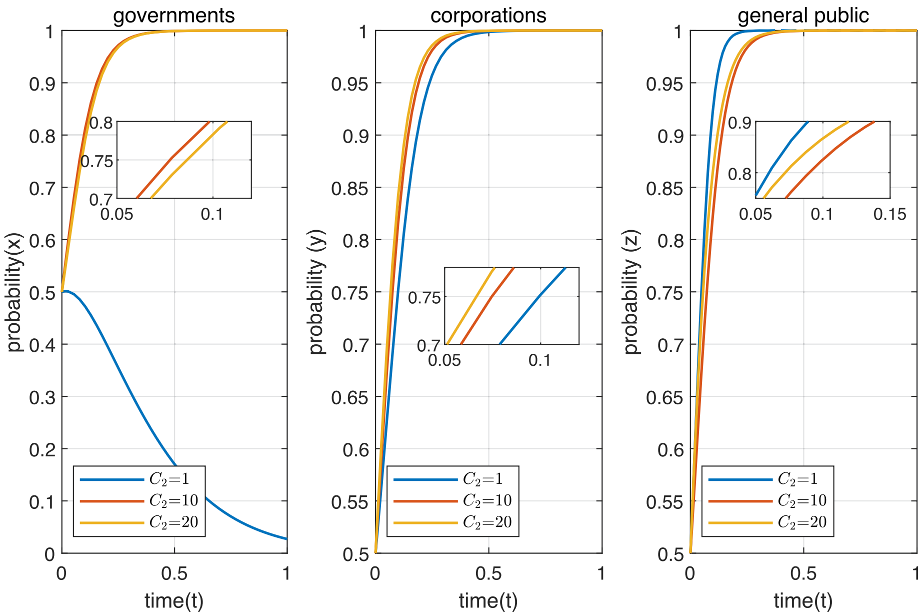

FIGURE 9. The effects of C_2 on ESS.

Interestingly, this upward trend in public adaptation probability slows when C_2 reaches a medium value at 10. This deceleration could be attributed to factors such as uncertainty in regulatory policies, higher barriers to participation, the absence of a formed social consensus, and the influence of media and public opinion.

4.3.2. Effect of the penalties for corporations

Similarly, to assess the impact of penalties (P) for corporations "traditional investments" on system dynamics and strategic choices, the sensitivity analysis systematically varies P across low, medium, and high levels, while keeping other parameters constant. As depicted in Figure 10, the trend towards the governments adopting "strict regulation" strategy becomes increasingly evident as P escalate to a maximum value of 30. This trend is driven not solely by the potential for increased fines, which incentivize stricter enforcement to prevent violations, but also by the pressures and expectations of the public. Corporations, aiming to avoid substantial fines, are more inclined to invest in a "green investments" strategy, with the trend becoming more pronounced as P increases from 10 to 30. However, the public's propensity to adapt shows a slowdown when P reaches a moderate level of 20. This deceleration mirrors patterns identified in previous analyses and may be attributed to factors such as uncertainties in regulatory policies, higher barriers to public participation, and the influence of media and public opinion.

4.3.3. Effect of the compensations for general public's losses

To assess the impact of compensations (S_2) for public losses due to corporate "traditional investments" on system dynamics and strategic choices, the sensitivity analysis varies S_2 systematically across low, medium, and high levels, while keeping other parameters constant. A comparison in Figure 11 indicates that when compensation for public losses is minimal, *e.g.*, S_2 at the lowest value of 2, there is a notable slowdown in the progress of corporate "green investments". Conversely, as S_2 increases, particularly reaching the maximum value of 10, substantial subsidies prompt corporations to reassess their investment strategies. This shift favors "green investments" as a more sustainable long-term approach, thereby accelerating the adoption of environmentally-friendly practices. A notable finding from this analysis is that higher S_2 values are associated with increased

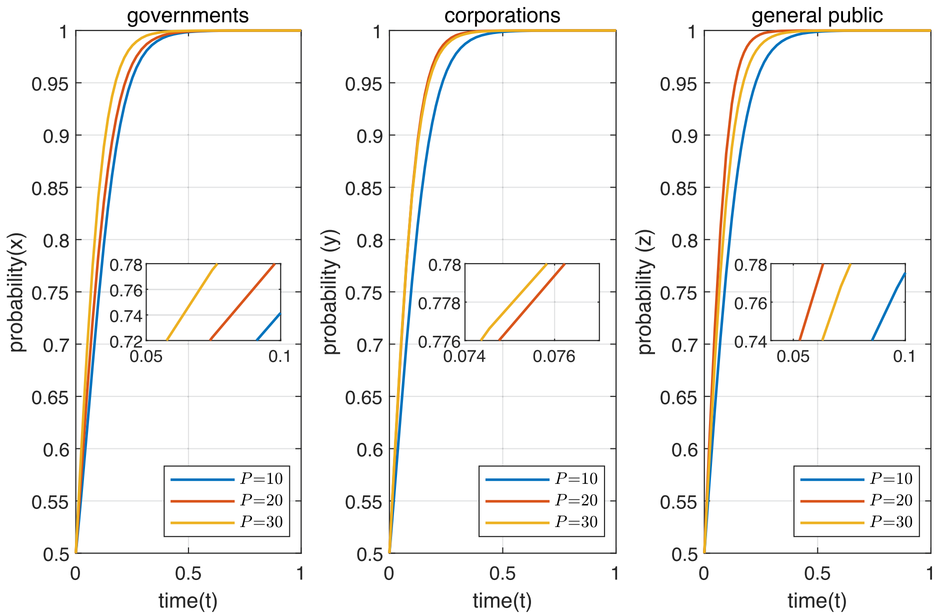

FIGURE 10. The effects of P on ESS.

public engagement. Unlike previous scenarios, a higher S_2 directly correlates with greater public involvement. In summary, while strategies such as “strict supervision”, “green investments”, and enhanced public “participation” consistently emerge, the duration of these decision-making processes tends to lengthen.

4.4. Empirical analysis

As a leading player in China’s express delivery industry, SF Express has consistently demonstrated a strong commitment to energy efficiency and consumption reduction since 2018. This dedication is evidenced by significant investments in environmental infrastructure and a strategic approach to internalizing environmental costs. SF Express has thoroughly integrated eco-friendly principles into all aspects of its operations, including packaging, shipping, and transshipment. In alignment with China’s ambitious “dual carbon” objectives, SF Express has developed a digital carbon management platform and a comprehensive carbon management system. These initiatives enable SF Express to meticulously monitor and manage its carbon emissions across various operational domains, thereby advancing its vision of a “zero carbon future”. Consequently, this study selects SF Express as a case study to examine the implementation of a “green investments” strategy and the adoption of low-carbon environmental practices. This selection provides a practical basis for further simulation and validation of the theoretical model previously analyzed.

Based on the data from the “China Environmental Monitoring Research Report 2021–2027”, the government incurred costs of approximately 153 million yuan in 2021 for monitoring activities such as emissions (C_1). This monitoring effort resulted in an anticipated regulatory revenue (W) of about 109.7 million yuan. Following the implementation of the “Public Participation in Environmental Protection Measures”[1], public involvement in supervising corporate non-environmentally friendly activities intensified, leading to government-issued supervision rewards (C_2) totaling approximately 162 million yuan. Additionally, according to the “Package Management Measures for Mail and Express Deliveries” implemented by China’s Ministry of Transport in 2021, an average penalty of 3000 yuan was imposed for each non-compliant package. In 2021, SF Express had 32 460 cases of

[1] https://www.gov.cn/gongbao/content/2015/content_2961714.htm.

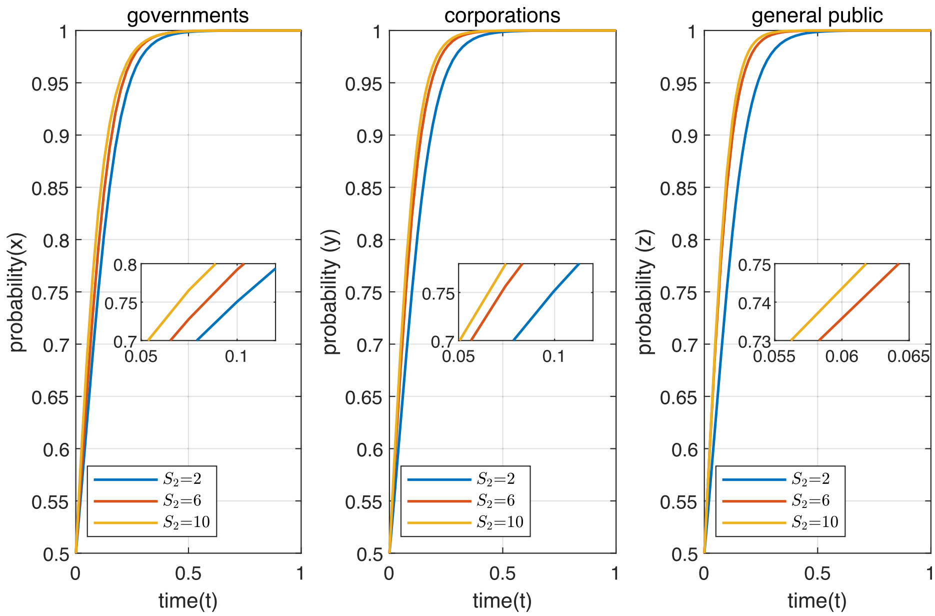

FIGURE 11. The effect of S_2 on ESS.

non-compliant packaging, resulting in a total penalty (P) of 97.4 million yuan, calculated as 3000 yuan per case multiplied by 32 460 cases.

Data from the "SF Holdings 2021 Annual Sustainability Report"[2] indicates that SF Express annually invested approximately 55 million yuan (C_3) in low-carbon and environmentally friendly initiatives, such as adopting renewable energy, using green, low-carbon packaging, and purchasing carbon offset credits. This commitment to environmental sustainability is projected to yield direct financial benefits (R_1) of approximately 203 million yuan for the company, along with a governmental subsidy (S_1) of about 0.9 million yuan. Conversely, non-adherence to these environmental principles obliges SF Express to incur costs (C_4) such as environmental fines and traditional energy expenses, totaling around 34.2 million yuan. Notably, by continuing traditional technological innovation, SF Express may also reap additional potential benefits. These benefits include reduced implementation costs, increased asset value, and heightened investor interest (R_2), which, based on the company's cost-profit ratio in 2021, is estimated to be around 126.2 million yuan.

In recent years, with increasing public enthusiasm for participating in environmental protection activities, individuals have reported corporate environmental violations through various channels such as the "National Ecological Environment Complaint and Report Platform", WeChat official accounts, and hotline calls. Drawing from Wang *et al.* [36], this study assumes the cost of public reporting per case is 550 yuan. Given that SF Express had approximately 32 460 instances of non-compliant packaging in 2021, the total public reporting cost (C_5) can be calculated as 550 yuan per case multiplied by 32 460 cases, amounting to 17.9 million yuan. Additionally, according to the provisions for atmospheric pollution in the "Ecological Environment Damage Compensation System Reform Plan"[3], businesses are required to pay compensation (S_2) for the impact of their carbon emissions on public resources, estimated at one million yuan. Furthermore, considering the rewards for reporting violations, the positive financial gains (R_3) for the public, including reporting rewards and the enhancement of satisfaction and self-esteem, are estimated to be around 162 million yuan.

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[2] https://www.sf-express.com/mobile/cn/sc/prd/sustainable/home.
[3] https://www.gov.cn/zhengce/2017-12/17/content_5247952.htm.

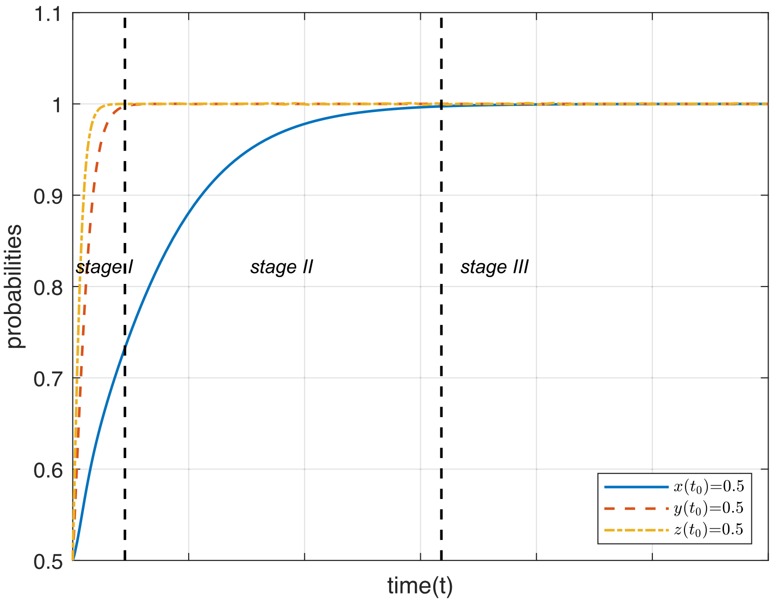

FIGURE 12. Evolutionary trajectory of stakeholders in the empirical analysis.

Consequently, integrating the specified variable data into the model allows for constructing a trajectory that delineates the evolving behaviors of stakeholders in SF Express's green investments initiative. This process is characterized by the collaborative engagement of both government and public entities. As illustrated in Figure 12, it is evident that SF Express's proactive approach to green investments has yielded significant achievements. On the other hand, a thorough analysis of these green investment practices substantiates the validity and precision of the previously discussed model. In essence, the progressive stages of SF Express's green investments, orchestrated through the synergistic participation of government and public sectors, can be systematically divided into three distinct phases.

Initial Stage. This stage is characterized by a notable increase in the probability of the government implementing "strict regulation". Concurrently, SF Express intensifies its commitment to environmentally friendly investments, while public participation in these initiatives grows, slightly outpacing corporate efforts. This trend likely stems from the public's capacity to reduce environmental harm through SF Express's sustainable investments, thus improving societal welfare. As a result, the public's active engagement becomes increasingly apparent. Facing heightened public scrutiny and a surge in environmental reporting, SF Express places greater emphasis on public opinion, aligning its strategies with the public's rising environmental concerns and actively investing in sustainability. For the government, this stage necessitates maximizing regulatory efforts to discourage corporate retreat from sustainable practices.

Transition Stage. During this phase, the strategic approaches of both the public and SF Express remain consistent and stable. Meanwhile, the probability of the government's "strict regulation" strategy continues to ascend, ultimately reaching its maximum. SF Express's eco-friendly actions, now yielding tangible benefits, also attract government subsidies for research and development, further solidifying their dedication to sustainable practices. Given the rising costs associated with lenient regulation and increased corporate penalties, the government escalates its regulatory actions. Additionally, due to robust public engagement, the government, as a service-oriented entity, progressively addresses public environmental demands through stricter regulations. In this scenario, the government's stringent regulatory posture becomes a vital protective measure for SF Express's sustainable investment strategy.

Maturity Stage. At this point, the government, SF Express, and the public attain a state of equilibrium, aligning with Scenario IV described in Section 4.2. Here, neither the public nor SF Express alter their strategic choices, and the government, after considering the benefits and drawbacks (such as potential profits or expenses), continues to strengthen regulation. This approach helps avoid numerous negative effects of non-regulation, such as loss of government credibility and trust, ultimately leading to a mutually beneficial situation for all parties involved.

5. Discussion

In the face of urgent global environmental challenges and the demands of sustainable development, corporate green investments are essential not only for demonstrating social responsibility but also for ensuring long-term economic viability. The impact of green investments on environmental and financial performance is complex due to their positive externalities and the nature of environmental governance as a public good. To understand corporate green investment behaviors, it is crucial to examine the relationship between governments regulation, public participation, and their combined influence on corporate green investments and economic benefits. This study integrates these elements – governments oversight, corporate investment strategies, and public involvement – into a comprehensive analytical framework. This framework aims to thoroughly investigate the nature and economic consequences of corporate green investments, providing insights into how these factors interact and contribute to sustainable business practices.

The analysis of a tripartite evolutionary game demonstrates that the equilibrium strategies, specifically E_2 and E_8, are determined by the combined decisions of governments and corporations. The strategy E_8 emerges as the favored choice for both entities when the corporation's total revenue is sufficient to offset opportunity costs and the governments' benefits from active regulation exceed those from passive approaches. Under these conditions, competitive regulatory efforts by governments positively influence the implementation of corporate green investments to a significant degree. This dynamic can drive governments to more stringently regulate corporations that neglect green investments, aiming to bolster their public image through performance appraisals. However, if either party prioritizes its own interests, it can lead to a suboptimal strategy, represented by E_2.

The simulation analysis results reveal that public behavior significantly impacts all four ESSs – E_2, E_4, E_6 and E_8. Public involvement can lead to more constructive interactions between governments and corporations. Specifically, active public monitoring can effectively prevent these entities from falling into a prisoner's dilemma, encouraging both to adopt more reasonable actions. Additionally, public supervision, functioning as a "soft constraint" mechanism, positively influences corporate green investments decisions. This effect extends beyond local corporations to neighboring regions with similar economic conditions, thereby enhancing the overall economic benefits of corporate green investments [7].

Variability in the costs associated with governments regulation may exert a notable impact on the outcomes of the tripartite evolutionary game. It is evident that during periods characterized by low regulatory costs, governments tend to favor supporting independent development initiatives and promoting innovation within corporations. In contrast, as these costs rise, governments are inclined to implement more stringent regulatory frameworks. However, it is imperative to underscore that these intensified regulations are predominantly grounded in collaborative efforts and persist in relying upon the proactive engagement of businesses. In particular, policy-makers are presently endeavoring to advance green economy strategies, moving beyond the traditional "firms versus state" approach in regulatory environmental politics [9]. These innovative approaches, often referred to as "smart policy mixes", extensively leverage cooperation between corporate entities and governments authorities, marking a significant departure from traditional command-and-control regulations [27].

Theoretical and simulation studies reveal that government-imposed penalties on corporate "traditional investments" can significantly influence the dynamics of the tripartite evolutionary game. To fully understand these impacts, it is crucial to analyze the specific context of China. The environmental regulatory framework under China's environmental policy system is characterized by regional disparities [17, 37]. In regions with lower levels of marketization, local governments interference, often driven by self-interest [16], can lead to reduced fine standards. This reduction encourages corporations to channel significant resources into traditional investments strategies, which are seen as offering quicker economic returns and may overshadow the need for long-term environmental sustainability. To safeguard the equitable interests of corporations with the need for environmental sustainability, it is essential for the governments to implement a well-balanced fine policy. Such a policy should deter non-compliance while minimizing adverse effects on corporate economic interests. Additionally, the governments should consider providing fiscal subsidies, tax incentives, and other supportive measures to improve the local industrial ecosystem. These measures can promote collaboration among corporations and support green investments projects, ultimately advancing sustainable economic practices.

The tripartite game-theoretic model highlights that compensations for public losses caused by corporate choices to pursue "traditional investments" are crucial in shaping the dynamics of the evolutionary game. Such investments often overlook their environmental and societal impacts, potentially undermining the long-term competitiveness of corporations. As public losses accumulate and environmental concerns intensify, corporations become increasingly aware of the risks and limitations of traditional investments. This awareness prompts them to reconsider their strategies and explore more sustainable development paths. Interestingly, this finding contrasts with the view of Kolcava and Bernauer [19], who argue that citizens may perceive companies as engaging in "greenwashing" – reducing their environmental impact only under external policy pressures rather than through genuine proactive measures. According to this perspective, citizens might oppose policy frameworks that involve both corporate and governments regulations due to doubts about the authenticity of corporate environmental commitments.

6. Conclusions

In recent years, the discourse surrounding CSR has garnered increasing attention, with a specific focus on the influence of green investments on corporate performance. As global environmental concerns continue to intensify, businesses are compelled to reassess their strategies, with a critical consideration given to the intersection of governments regulation and public participation in shaping sustainable practices. This study employs a robust tripartite evolutionary modeling approach to thoroughly examine the intricate decision-making processes of stakeholders engaged in corporate green investments, including governments entities and the public. Subsequently, through the utilization of the proposed replicated dynamic equations, this study delves into the ESSs employed by the tripartite mainstay. Additionally, a numerical investigation is conducted to validate the findings, drawing insights from a real-world example.

This study contributes to understanding corporate green investments and yields several key findings. First, the game model reveals the presence of eight equilibrium points and identifies four potential ESSs. The selection of each ESS is primarily contingent upon the cost and revenue trade-offs of individual stakeholders. In essence, the strategic decisions made by the three main stakeholders regarding the green investments scheme signify a continuous and dynamic interaction and optimization process. Second, the escalation in governmental regulatory costs not only propels the governments to shift its behavioral strategies but also incentivizes corporations to augment their green investments. Additionally, the continuous increase in penalties plays a pivotal role in prompting corporations to favor green investments options. Lastly, recognizing compensatory responsibilities for public losses steers corporations toward seeking more sustainable development pathways.

This study acknowledges the presence of limitations that necessitate further exploration. Despite governments initiative to advance green development through various policies, the potential variability in policies such as tax incentives and environmental subsidies introduces challenges for companies striving to maintain a stable, long-term implementation of green investments strategies. Additionally, as a complex system, the stability of enacting green investments strategies depends on both external collaboration and internal coordination among shareholders, creditors, and operators, emphasizing the need for further investigation in future research.

Appendix A. The solutions of the dynamic replication equations

A.1. Solutions of the governments' dynamic replication equation

When governments choose the "strict regulation" strategy, the expected payoff is U_1, giving:

$$\begin{aligned} U_1 &= yz\,(-C_1 - S_1) + (1-y)z[\mu_1\,(W+P) - C_1 + \mu_2 W] \\ &+ y\,(1-z)\,(-C_1 - S_1) + (1-y)(1-z)[\mu_1\,(W+P) - C_1]. \end{aligned} \tag{A.1}$$

When governments adopt the "passive regulation" strategy, the expected payoff becomes U_2, giving:

$$U_2 = yz\,(-C_2 - S_1) + (1-y)\,z\,[\mu_2\,(W+P) - C_2] + y(1-z)\,(-C_2)\,. \tag{A.2}$$

Then, $\bar{U}_{12}$ can be interpreted as the average expected payoff of governments that adopt the former two strategies, then:

$$\bar{U}_{12} = xU_1 + (1-x)U_2. \tag{A.3}$$

A.2. Solutions of corporations' dynamic replication equation

Similarly, when corporations adopt the "green investments" strategy, the expected payoff can be denoted as U_3, while the expected payoff for the "traditional investments" strategy can be denoted as U_4:

$$\begin{aligned} U_3 &= xz\,(R_1 - C_3 + S_1) + (1-x)\,z\,(R_1 - C_3 + S_1) \\ &+ x(1-z)(R_1 - C_3 + S_1) + (1-x)(1-z)(R_1 - C_3) \end{aligned} \tag{A.4}$$

$$\begin{aligned} U_4 &= xz\,[(1-\mu_1)\,R_2 - \mu_1\,(P + C_4 + S_2)] + (1-x)\,z\,[(1-\mu_2)\,R_2 - \mu_2\,(P + C_4 + S_2)] \\ &+ x(1-z)\,[(1-\mu_1)R_2 - \mu_1\,(P + C_4 + S_2)] + (1-x)(1-z)\,(R_2 - C_4 - S_2)\,. \end{aligned} \tag{A.5}$$

Then, $\bar{U}_{34}$ can be interpreted as the average expected payoff of corporations that adopt the former two strategies, as follows:

$$\bar{U}_{34} = yU_3 + (1-y)U_4. \tag{A.6}$$

A.3. Solutions of the general public's dynamic replication equation

Assuming U_5 and U_6 represent the expected payoffs of the public adopting the "participation" and "non-participation" strategies, respectively; $\bar{U}_{56}$ can be interpreted as the average expected payoff of the public adopting either of these two strategies, as follows:

$$\begin{aligned} U_5 &= xyR_3 + x(1-y)\,(\mu_1 S_2 + R_3 - C_5) + (1-x)y(R_3 + C_2 - L) \\ &+ (1-x)(1-y)(\mu_2 S_2 + R_3 + C_2 - C_5 - L) \end{aligned} \tag{A.7}$$

$$U_6 = x\,(1-y)\,\mu_1 S_2 - (1-x)\,yL + (1-x)\,(1-y)\,(S_2 - L) \tag{A.8}$$

$$\bar{U}_{56} = zU_5 + (1-z)\,U_6. \tag{A.9}$$

Appendix B. The stability analysis of stakeholders

B.1. Stability of the governments' strategy choice

When $F(x) = 0$, $z = z^* = \frac{C_1 - \mu_1(W+P) - y[C_2 - \mu_1(W+P) - S_1]}{y(\mu_2 P - C_1 + S_1) - \mu_2 P + C_2}$ holds, indicating that all game strategies are in a steady state.

If $z \neq z^*$, supposing $F(x) = 0$, then $x = 0$ and $x = 1$ are two stable points. The derivative of the replicator dynamics equation $F(x)$ can be further calculated as follows:

$$\begin{aligned} F^{'}(x) = \frac{\mathrm{d}F(x)}{\mathrm{d}t} &= (1-2x)\,\{yz\,(\mu_2 P - C_1 + S_1) + y[C_2 - \mu_1(W+P) - S_1] \\ &+ z\,(C_2 - \mu_2 P) + \mu_1\,(W+P) - C_1\}\,. \end{aligned} \tag{B.1}$$

According to the nature of the ESS, the necessary condition for the government group to achieve evolutionary stability is $F^{'}(x) < 0$. Different circumstances can be analyzed separately according to equation (B.1):

When $yz(\mu_2 P - C_1 + S_1) + y[C_2 - \mu_1(W+P) - S_1] + z(C_2 - \mu_2 P) < \mu_1(W+P) - C_1$, it can be derived that $yz(\mu_2 P - C_1 + S_1) + y[C_2 - \mu_1(W+P) - S_1] + z(C_2 - \mu_2 P) + \mu_1(W+P) - C_1 < 0$ holds, $F'(x)|_{x=0} < 0, F'(x)|_{x=1} > 0$. Thus, $x = 0$ is ESS.

When $yz(\mu_2 P - C_1 + S_1) + y[C_2 - \mu_1(W+P) - S_1] + z(C_2 - \mu_2 P) > \mu_1(W+P) - C_1$, then:

If $0 < z < z^*$, $F'(x)|_{x=0} < 0$ and $F'(x)|_{x=1} > 0$. Thus, $x= 0$ is ESS, and governments tend to choose the "passive regulation" strategy.

If $z^* < z < 1$, $F'(x)|_{x=0} > 0$ and $F'(x)|_{x=1} < 0$. Thus, $x= 1$ is ESS, and governments tend to choose the "strict regulation" strategy.

B.2. Stability of the corporate strategy choice

When $F(y) = 0$, $z = z^* = \frac{-x[\mu_1(R_2+P+C_4+S_2)+S_1-C_4-S_2]-R_1+C_3-S_2+R_2-C_4}{(1-x)[\mu_2(R_2+P+C_4+S_2)+S_1-C_4-S_2]}$ holds, indicating that all game strategies are in a steady state.

When $z \neq z^*$, supposing $F(y) = 0$, then $y = 0$ and $y = 1$ are two stable points. The derivative of the replicator dynamics equation $F(y)$ can be further calculated as follows:

$$\begin{aligned} F'(y) = \frac{\mathrm{d}F(y)}{\mathrm{d}t} &= (1-2y)\{-xz[\mu_2(R_2+P+C_4+S_2) + S_1 - C_4 - S_2] \\ &+x[\mu_1(R_2+P+C_4+S_2) + S_1 - C_4 - S_2] + z[\mu_2(R_2+P+C_4+S_2) \\ &+S_1 - C_4 - S_2] + (R_1 - C_3 + S_2 - R_2 + C_4)\}. \end{aligned} \tag{B.2}$$

Similarly, the necessary condition for the corporate group to achieve an evolutionarily stable strategy is $F^{'}(y) < 0$. Different circumstances can be analyzed separately according to equation (B.2):

When $-xz[\mu_2(R_2+P+C_4+S_2)+S_1-C_4-S_2]+x[\mu_1(R_2+P+C_4+S_2)+S_1-C_4-S_2]+z[\mu_2(R_2+P+C_4+S_2)+S_1-C_4-S_2] < R_1 - C_3 + S_2 - R_2 + C_4$, under the premise of $< x, y, z < 1$, it can be derived that $-xz[\mu_2(R_2+P+C_4+S_2)+S_1-C_4-S_2]+x[\mu_1(R_2+P+C_4+S_2)+S_1-C_4-S_2]+z[\mu_2(R_2+P+C_4+S_2)+S_1-C_4-S_2]+(R_1-C_3+S_2-R_2+C_4) < 0$ holds, $F'(y)|_{y=0} < 0, F'(y)|_{y=1} > 0$. Thus, $y = 0$ is ESS.

When $-xz[\mu_2(R_2+P+C_4+S_2)+S_1-C_4-S_2]+x[\mu_1(R_2+P+C_4+S_2)+S_1-C_4-S_2]+z[\mu_2(R_2+P+C_4+S_2)+S_1-C_4-S_2] > R_1 - C_3 + S_2 - R_2 + C_4$, then:

If $0 < z < z^*, F'(y)|_{y=0} < 0$ and $F'(y)|_{y=1} > 0$. Thus, $y = 0$ is ESS and corporations tend to choose the "traditional investments" strategy.

If $z^* < z < 1$, $F'(y)|_{y=0} > 0$ and $F'(y)|_{y=1} < 0$. Thus, $y = 1$ is ESS, and corporations tend to choose the "green investments" strategy.

B.3. Stability of the public's strategy choice

When $F(z) = 0$, $y = y^* = \frac{x[C_2-(1-\mu_2)S_2]-R_3-\mu_2 S_2-C_2+C_5+S_2}{\mu_2 S_2(x-1)+S_2+C_5}$ holds, indicating that all game strategies are in a steady state.

When $y \neq y^*$, supposing $F(z) = 0$, then $y = 0$ and $y = 1$ are two stable points. The derivative of the replicator dynamics equation $F(z)$ can be further calculated as follows:

$$\begin{aligned} F^{'}(z) = \frac{\mathrm{d}F(z)}{\mathrm{d}t} &= (1-2z)\{xy\mu_2 S_2 + x[(1-\mu_2)S_2 - C_2] \\ &+ y[(1-\mu_2)S_2 + C_5] + R_3 + \mu_2 S_2 + C_2 - C_5 - S_2\}. \end{aligned} \tag{B.3}$$

Similarly, different circumstances can be analyzed separately according to equation (B.3):

When $xy\mu_2 S_2 + x[(1-\mu_2)S_2 - C_2] + y[(1-\mu_2)S_2 + C_5] + R_3 < \mu_2 S_2 + C_2 - C_5 - S_2$, under the premise of $< x, y, z < 1$, it can be derived that $xy\mu_2 S_2 + x[(1-\mu_2)S_2 - C_2] + y[(1-\mu_2)S_2 + C_5] + R_3 + \mu_2 S_2 + C_2 - C_5 - S_2 < 0$ holds, $F'(z)|_{z=1} < 0$, $F'(\mathrm{z})|_{z=0} > 0$. Thus, $z= 0$ is ESS.

When $xy\mu_2 S_2 + x\left[(1-\mu_2) S_2 - C_2\right] + y\left[(1-\mu_2) S_2 + C_5\right] + R_3 > \mu_2 S_2 + C_2 - C_5 - S_2$, then:

If $0 < y < y^*$, $F'(z)|_{z=0} > 0$ and $F'(z)|_{z=1} < 0$. Thus, $z = 1$ is ESS, and the public chooses the "participation" strategy.

If $y^* < y < 1$, $F'(z)|_{z=0} < 0$ and $F'(z)|_{z=1} > 0$. Thus, $z = 0$ is ESS, and the public chooses the "non-participation" strategy.

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