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How to govern greenwashing behaviors in green finance products: a tripartite evolutionary game approach

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Abstract

Greenwashing behaviors (GWBs) in green finance products (GFPs) by enterprises seriously hinder the realization of environmental protection goals. However, methods for effectively regulating GWBs in GFPs are unclear. This study constructed a tripartite evolutionary game model to analyze the formation and governance mechanisms of GWBs in GFPs among regulatory authorities, enterprises, and investors. Subsequently, the stability equilibrium strategy and key factors influencing the system equilibrium were discussed. Several interesting conclusions were drawn. First, we demonstrated that an interdependence mechanism exists among three game agents who mutually influence each other. The larger the probability of regulatory authorities choosing active supervision and investors adopting feedback, the more enterprises are willing to carry out green projects. Second, three corresponding governance modes for GWBs were put forward following the developmental stages of GFPs. Among these, the collaboration mode is the most effective in incentivizing enterprises to implement green projects. Third, based on sensitivity simulations, the initial willingness of the tripartite stakeholders, investor feedback cost, investor compensation, the penalty for greenwashing enterprises, and the reputational benefit of enterprises are critical factors that influence evolutionary results. Finally, targeted countermeasures were provided for regulatory authorities to prevent enterprises from engaging in GWBs.

Keywords: Evolutionary game, Green finance product, Greenwashing behaviors, Investor feedback

Introduction

Sustainable finance has emerged as a key tool for the integration of finance activities and sustainable development goals. The scope of sustainable finance is very broad, including green finance, carbon finance, and climate finance (Kumar et al. 2022). As the most dominant area of sustainable finance, green finance is perceived as one of the most efficient ways to promote the coordinated development of environmental sustainability and economic growth (Croutzet and Dabbous 2021; Geng et al. 2021; Li et al. 2021). In recent years, the rapid emergence of financial technologies, such as big data, artificial intelligence, and blockchain, has accelerated innovation in green finance products (GFPs) (Goodell et al. 2021; Lv et al. 2022). As innovative investing instruments, GFPs play an important role in reducing carbon emissions, which have experienced rapid growth worldwide (Akomea-Frimpong et al. 2022; Chen et al. 2023a). Different types of GFPs, such as green bonds, green stocks, and green credit, have been issued (Bhutta et al. 2022). The United States provided US$1 billion worth of international climate finance in 2022. In 2021, the cumulative green bond issuance now amounts to US$ 26.15 billion in Japan (Peng et al. 2022). In 2020, the new issuance of green bonds in China amounted to US$ 44.07 billion (Xu et al. 2022a). Facing tremendous pressure from environmental regulations and financial burdens, enterprises pursue GFPs because of their diverse benefits. On the one hand, GFPs offer important financial support for enterprises to invest in green projects (Liu et al. 2021b). On the other hand, GFPs also contribute to dealing with the challenges of climate change and environmental degradation.

However, some enterprises offer GFPs without truly investing in green projects; instead, they disclose environmental information speculatively or even misreport environmental behaviors, leading to the spread of greenwashing behaviors (GWBs) (Yu et al. 2020). The GWBs of such enterprises reveal a mismatch between GFPs and green projects, i.e., they obtain GFPs without taking substantial environmental action. Because the GWBs of GFPs often happen in renewable or energy-efficient projects, enterprises usually deceptively announce carbon emission data but do not effectively implement projects accordingly. For example, environmental, social, and governance (ESG) disclosure information has become the main form of greenwashing in practice (Lim et al. 2022). Moreover, the consequences of GWBs in GFPs are more serious, which lowers emission reduction efficiency, misleads investors, and even leads to green financial risk (Yu, et al. 2020). Regarding the significant information asymmetry and lack of adequate resources, regulatory authorities may not sufficiently monitor the use of GFPs and the quality of green projects. This recurrence of GWBs has demonstrated that severe regulatory loopholes regarding GWBs exist in practice (Liu et al. 2022b). In 2020, the Climate Bond Initiative reported that, in China, about 45.8% of new issuances of green bonds did not follow internationally accepted definitions, providing enormous potential for GWBs. The GWBs of enterprises have a significant negative impact that severely hampers the realization of environmental protection goals and poses huge risks to the green finance market (Xu et al. 2022b). The diversification effects and role of GFPs only exist when there is no fear of GWBs (Nanayakkara and Colombage 2019). Therefore, curbing the GWBs of enterprises has become a major challenge for regulators, so the regulations of GWBs in GFPs should be explored from a governance perspective.

In GFPs-related research, scholars have mainly examined the impact of GFPs on stock market reactions (Naeem et al. 2022), corporate operations (Sharma et al. 2021), firm performance (Flammer 2021), and economic development (Yin and Xu 2022). However, the existing literature makes little effort to investigate governance strategies for GWBs in GFPs. Furthermore, to regulators, as important stakeholders in GFPs, investors maintain a vital interest in enterprises through financing and investment (Huynh et al. 2020). Furthermore, the introduction of investor supervision can facilitate the sustainable development of GFPs. However, the regulatory synergy of investors in GFPs has often been neglected (Martin and Moser 2016). GWBs in GFPs involve regulatory authorities, investors, and enterprises with different objectives. This makes the governance of GWBs a complex issue (Akomea-Frimpong, et al. 2022). Therefore, a highly effective GWBs regulation mechanism for GFPs that includes investors needs to be constructed urgently.

As the three participating subjects—regulatory authorities, investors, and enterprises—have heterogeneous interests, an exploration of the decision-making behavior of stakeholders is key to examining how to supervise GWBs. Against this background, a discussion of the governance of GWBs in GFPs requires answering several research questions, including the following:

1. From a multiple-stakeholder perspective, how can the interests of regulatory authorities, investors, and enterprises be coordinated in regulating GWBs in GFPs?
2. How does the decision-making behavior of investors affect the strategic choices of regulatory authorities and enterprises?
3. What are the key factors that affect regulatory authorities, investors, and enterprises in minimizing GWBs in GFPs?

In answering the questions posed above, this study makes novel contributions to the literature in the following ways:

1. An entirely new perspective on the regulation of GWBs in GFPs is provided. The different governance roles of stakeholders in the green finance market remain largely unexplored. To fill this gap, unlike previous literature, which mainly analyzes the role of regulators, in addition to considering regulatory authorities, this study introduces investor feedback as a factor in the process of enterprise adoption of GWBs. Moreover, measures to enhance investor engagement in supervision are further proposed, thereby enriching the literature on the prevention of GWBs and the effectiveness of regulations on GWBs.
2. Three governance modes for GWBs with respect to the different developmental stages of GFPs have been put forward. Previous studies have ignored the characteristics of GFPs at different stages. As a result, regulatory measures targeting GWBs have not always been effective in combating them (Johnsson et al. 2020; Siano et al. 2017). In this study, by analyzing evolutionarily stable strategies, corresponding to the different developmental stages of GFPs, three governance modes are established—mandatory mode, incentive mode, and collaboration mode. These modes can provide a crucial reference for regulators to select the governance mode in a certain period.
3. The application of an evolutionary game model was expanded to the governance of GFPs. To the best of our knowledge, this is a novel application of the evolutionary game model to the governance of GWBs in GFPs. The evolutionary game integrated three stakeholders—regulatory authorities, investors, and enterprises—into one model, providing an effective tool for investigating the interactions among the different stakeholders. In addition, the factors of the behavioral characteristics of participants were also investigated in depth through numerical simulation. The conclusion is conducive to formulating policy decisions and governance measures to prevent GWBs.

The remainder of this paper proceeds as follows. Section "Related literature" presents the related literature. In Section "Model setup", we describe the problem, propose our assumptions, and build the evolutionary game model. Section "Model analysis" provides an analysis of the evolutionary stability of the three stakeholders in detail. In Section "Numerical simulation", we present our numerical simulation. In Section "Conclusions, policy recommendations, and limitations", the conclusions and policy recommendations are presented.

Related literature

This study mainly focuses on the GWBs of enterprises in GFPs. The related literature primarily investigated green finance development, the regulation of GWBs, and the application of the evolutionary game theory in regulation.

Ever since the emergence of green finance, its main goal has been to provide financial support for green projects with environmental benefits, such as environmental protection and clean energy (Jones et al. 2020; Liu et al. 2023b; Meng et al. 2021; Rao et al. 2021). Many studies have discussed the application and effects of green finance from the macro level and explored the effects of the implementation of green finance. Ibrahim et al. (2022) examined the impact of green finance, technological innovation, and economic complexity on the criticality of renewable energy for sustainable development. Zhang (2022b) revealed that green finance in renewable energy projects has a positive relationship with economic growth. Regarding the impacts on the control of climate change, Wang et al. (2022a) examined the effect of green bond issuance on firms' climate risk concerns from 2011 to 2020. However, the development of GFPs still faces a series of challenges—one is that the key participants have heterogeneous interests (Cui et al. 2020). Therefore, the development problems of GFPs should be discussed with the stakeholder theory, which is the theoretical lens of this study.

To maintain the healthy development of green finance, regulation in the context of the green finance market has been explored (Ding et al. 2022; Zha et al. 2020). Some scholars have begun to focus on the impact of GWBs on GFPs. For instance, Zhang (2022a) estimated the greenwashing risk of extreme events in the form of green financial system regulation shock, finding that green financial regulation makes highly polluting firms more likely to engage in greenwashing. Xing et al. (2021) investigated how, due to corporate greenwashing, firms with higher environmental disclosure quality do not obtain more loans. Only green innovation promotes access to corporate loans. Baldi and Pandimiglio (2022) discussed the role of ESG scoring and greenwashing risk in green bonds. They discovered that investors are willing to underwrite green bonds issued by local governments and service firms to minimize their exposure to greenwashing risk. Lee and Raschke (2023) took this conclusion one step further, revealing that firms with low ESG performance are more likely to engage in greenwashing to guarantee their access to green finance. Many studies have examined the characteristics and hazards of greenwashing enterprises. However, the formation and governance process of GWBs in GFPs are rarely discussed.

Regarding the solution to the problems of GWBs in GFPs, at present, some scholars have proposed regulation as the most favorable approach, especially the establishment of a multiparty supervision mechanism (Xu, et al. 2022b). Regarding multiagent regulation problems, the evolutionary game theory has proven to be an effective method (Dong et al. 2022; Liu et al. 2021a; Wang et al. 2022b); it has been widely used to explore the behaviors of multi-stakeholder systems, such as the e-waste recycling industry (Wang et al. 2020), industrial pollution control (Fan et al. 2021), the gasoline-powered vehicle industry (Liu and Dong 2022), the green building supply market (Chen et al. 2023b; Liu et al. 2022a), and the coal industry (Xu et al. 2019). Furthermore, due to the advantages of dynamic strategic analysis, the evolutionary game is regarded as an effective tool to apply to GWBs governance in different fields. For example, in construction projects, He et al. (2020) adopted a two-stage game theory perspective to explore contractor GWBs. In the production of electric vehicles, Liu et al. (2023a) constructed a tripartite evolutionary game model to research manufacturers' GWBs. Using a multiparty game, Ma et al. (2021) considered the organic food supply chain and analyzed regulations on corporate social irresponsibility. From the perspective of developing countries, Huang et al. (2020) conducted a game-theoretical exploration of firms, customers, and government regulations to combat greenwashing by firms. The above analysis reveals that evolutionary game enables the application of mathematical models to investigate GWBs.

Regarding the combat of GWBs in GFPs, the related research is still in the initial stage. Many studies have focused on greenwashing in ESG and empirically explored the quality of disclosures and regulation (Becker et al. 2022; Marquis et al. 2016), e.g., the characteristics of enterprises engaged in ESG greenwashing (Cronin and Doyle-Kent 2022), the impact on investment decisions (Chen and Xie 2022), and ESG disclosure defect (Friede 2019). Therefore, it is difficult for regulatory authorities and investors to directly evaluate enterprises' environmental performance. However, very few studies have explored the regulation of GWBs in GFPs from a governance perspective, so our goal is to fill this research gap.

The literature review reveals that previous research mainly focused on a functional description and the operating mechanism of GFPs, while regulations on GFPs are rarely considered. Even how GWBs represent an important obstacle to the implementation of green finance is not fully explored. Moreover, existing studies have paid little attention to specific supervisory suggestions regarding GWBs, which are the focus of this study. Regarding the game theory, it has been widely applied in multiparty contexts for the goal of supervision. However, a combination of the evolutionary game theory with the GWBs of GFPs is absent in the existing literature. The patterns of GWB in GFPs are closely related to the research framework mentioned above (Xu et al. 2020). Therefore, in this study, first, based on the stakeholder theory, we investigate the interactions among three different stakeholders—regulatory authorities, enterprises, and investors. Additionally, we utilize a tripartite evolutionary game to explore the strategy behavior and the incentive mechanism. Moreover, governance modes and policies are suggested according to the game and its numerical results. Table 1 presents several related studies, revealing their content and relevance.

Model setup

Problem description

The theoretical lens of this study is the stakeholder theory, which suggests that enterprises' activities are mainly affected by pressure from external stakeholders (Cooper

Table 1 Related literature and their relevance to our study

Authors	Green finance	Investor feedback	Greenwashing behavior	Evolutionary game	Multi-party
Zhang (2022b)	✓		✓		✓
He et al. (2020)			✓	✓	✓
Baldi and Pandimiglio (2022)	✓	✓	✓		
Huang et al. (2020)			✓	✓	✓
Xu et al. (2020)				✓	✓
This paper	✓	✓	✓	✓	✓

The symbol ✓ indicates that the paper includes a corresponding topic

et al. 2018). Regulatory authorities and investors are the two major stakeholders of enterprises in GFPs (Wang, et al. 2020). Therefore, the interactive relationship between them should be explored.

For enterprises, the pursuit of the maximum economic benefits of GFPs is an inevitable choice. Enterprises issue GFPs according to specific criteria of regulatory authorities, disclosing their environmental information through reports that include financial and implementation information (Schumacher 2019). However, because green projects are characterized by enormous costs, long return periods, and little practical supervision, enterprises that engage in poor environmental behaviors might take risks and make illegal use of GFPs. Ultimately, enterprises decide to engage in GWBs to generate greater proceeds.

Regulatory authorities act as the most direct agents in the prevention of GWBs by formulating policies and ensuring the quality of GFPs (Sun and Zhang 2019). However, considering regulation cost and capacity, weak governance by regulatory authorities can elicit deceptive behaviors. Thus, GWBs are prone to happen due to the intentional concealment of enterprises.

The demands of investors include an increase in the revenue of GFPs and the protection of their legitimate rights. As investors ultimately bear the risks of GFPs, they should also take the initiative to supervise the GWBs of enterprises (Sangiorgi and Schopohl 2021). Therefore, regulators should incentivize investors to participate in the coordinated regulation of GFPs.

In summary, the GWBs of enterprises can be viewed as a strategy adapted in response to the institutional pressure exerted by regulators and investors. Due to the relationships between the subjects of GFPs (see Fig. 1), each participant's activities are mainly affected by and constantly adjusted according to the decisions of other subjects. Consequently, GWBs governance in GFPs is a multistage and dynamic process. In the next section, we develop a tripartite evolutionary game model for further study.

Model assumptions and parameters

Considering the behavioral characteristics of regulatory authorities, enterprises, and investors in GFPs and incorporating GWBs, reasonable assumptions for a tripartite evolutionary game model are proposed below.

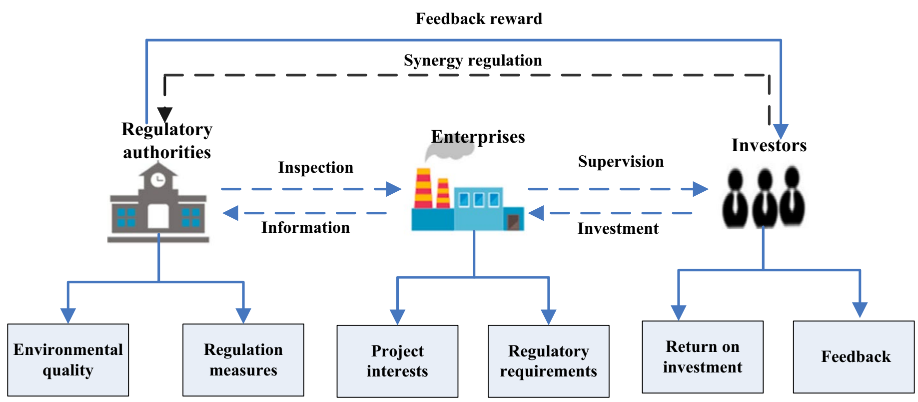

Fig. 1 Stakeholder relationships in GFPs

Assumption 1 The parties in this game model all exhibit bounded rationality. All parties adjust their strategies and imitate each other. The strategy choice evolves over time t and gradually stabilizes with the maximization of profits.

Assumption 2 Each stakeholder has two strategies. Investors have the option to give feedback on the quality of GFPs or not; the probability of feedback is assumed to be α, and that of non-feedback is $1-\alpha$. Similarly, enterprises have two possible strategies, namely, the probability of investing in green projects is β and the probability of choosing greenwashing projects is $1-\beta$. There are also two strategies for regulatory authorities—active supervision or passive supervision, and the corresponding probabilities are γ and $1-\gamma$ respectively.

Assumption 3 The benefit that regulatory authorities can obtain by reducing the risk of GFPs through active supervision is R_r, and the supervision cost is C_r, including the cost of collecting, evaluating, and reporting relevant supervision information (Liu and Xia 2020). The reputational losses of regulatory authorities when choosing passive supervision are L_r.

Assumption 4 The benefit of enterprise investment in green projects is V_e; the cost of green projects is $C_e = \frac{1}{2}cg_1^2$ (e.g., research on green innovation technology to discover more information on green projects); c is the cost coefficient; and the quality of green projects is g_1 (Gouda et al. 2016).

Assumption 5 When enterprises invest in green projects, a reputational return of enterprises R_e is obtained from investor feedback (e.g., the recognition of brand and image). When enterprises choose GWBs after obtaining GFPs, they will receive a penalty of F_e once the GWBs are detected, which will be considered as revenue by regulatory authorities. The losses to social welfare caused by GWBs are denoted as L_s.

Assumption 6 When investors engage in the supervision of GWBs in GFPs, the economic incentive from regulatory authorities is denoted as R_i. The cost of investor feedback is C_i, including time and economic costs. The compensation from enterprises to investors for GWBs is L_e, while the losses incurred by investors investing in greenwashing projects is L_i. Based on the above assumptions, the various parameters related to the model are summarized in Table 2.

Table 2 Model parameters and descriptions

Parameters	Descriptions	Range
$\alpha, 1-\alpha$	Probability of the investors choosing feedback or non-feedback	$0 \leq \alpha \leq 1$
$\beta, 1-\beta$	Probability of the enterprises investing in green projects or greenwashing projects	$0 \leq \beta \leq 1$
$\gamma, 1-\gamma$	Probability of the regulatory authorities' active supervision or passive supervision	$0 \leq \gamma \leq 1$
V_e	Profit of the enterprises' investment in green projects	$V_e > 0$
R_e	Reputational benefits of enterprises from investors for green projects	$R_e > 0$
C_e	Cost of enterprises for green projects	$C_e > 0$
F_e	Penalty for enterprises carrying out greenwashing projects	$F_e > 0$
g_1	Quality of green projects	$g_1 > 0$
R_i	Economic incentive for investor feedback	$R_i > 0$
C_i	Cost of investors choosing feedback	$C_i > 0$
L_i	Losses by investors investing in greenwashing projects	$L_i > 0$
L_e	Compensation from enterprises to investors	$L_e > 0$
R_r	Benefit of regulatory authorities from active supervision	$R_r > 0$
C_r	Cost of regulatory authorities' active supervision	$C_r > 0$
L_s	Social welfare losses caused by greenwashing projects	$L_s > 0$
L_r	The reputational losses of regulatory authorities' passive supervision	$L_r > 0$

Model construction

Eight strategies can be formulated in accordance with the three parties' options. The tripartite game tree is shown in Fig. 2.

Under the corresponding strategic combinations, the payoff matrix of investors, enterprises, and regulatory authorities is established in Table 3.

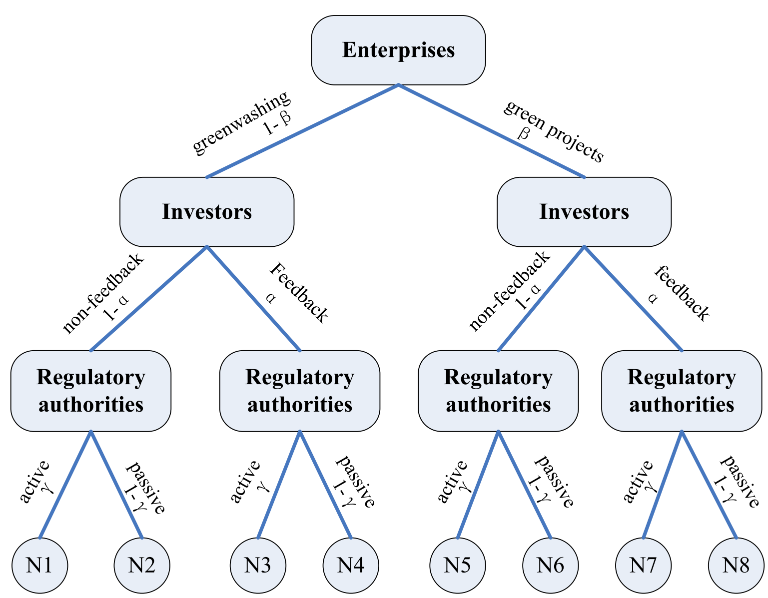

Fig. 2 The tripartite game

Table 3 Payoff matrix of the tripartite game

Participants		Investors	Enterprises	
			Green projects β	Greenwashing projects $1-\beta$
Regulatory authorities	Active supervision γ	Feedback α	$R_i - C_i$ $V_e + R_e - \frac{1}{2}cg_1^2$ $R_r - C_r - R_i$	$L_e + R_i - C_i$ $V_e - L_e - F_e$ $F_e + R_r - C_r - R_i$
		Non-feedback $1-\alpha$	0 $V_e - \frac{1}{2}cg_1^2$ $-C_r$	$-L_i$ $V_e - F_e$ $F_e - C_r$
	Passive supervision $1-\gamma$	Feedback α	$-C_i$ $V_e + R_e - \frac{1}{2}cg_1^2$ 0	$-C_i - L_i$ V_e $-L_r - L_s$
		Non-feedback $1-\alpha$	0 $V_e - \frac{1}{2}cg_1^2$ 0	$-L_i$ V_e $-L_s$

The order is the revenue of investors, enterprises, and regulatory authorities

Model analysis

Asymptotic stability analysis of the three parties

(1) Stability analysis of investor strategy

The expected benefit when investors choose the feedback strategy is

$$E_{11} = \beta\gamma(R_i - C_i) + \beta(1-\gamma)(-C_i) + \gamma(1-\beta)(L_e + R_i - C_i) + (1-\beta)(1-\gamma)(-C_i - L_i). \tag{1}$$

The expected benefit when investors choose the non-feedback strategy is

$$E_{12} = \beta\gamma 0 + \gamma(1-\beta)(-L_i) + (1-\gamma)\beta 0 + (1-\beta)(1-\gamma)(-L_i). \tag{2}$$

The average expected benefit of investors is

$$\overline{E_1} = \alpha E_{11} + (1-\alpha)E_{12} = (1-\beta)(\alpha\gamma L_e + \alpha\gamma L_i - L_i) + \alpha\gamma R_i - \alpha C_i. \tag{3}$$

The replicator dynamic equation of investors $F(\alpha)$ is

$$F(\alpha) = d\alpha\big/dt = \alpha\left(E_{11} - \overline{E_1}\right) = \alpha(1-\alpha)[\gamma(1-\beta)(L_e + L_i) + \gamma R_i - C_i]. \tag{4}$$

According to the stability theorem, the probability of investors choosing feedback behavior is in a stable state when both $F(\alpha) = 0$ and $dF(\alpha)\big/d\alpha = 0$ are satisfied, where α is the evolutionary stable point (ESP) (Wang et al. 2021).

The first derivative of α is $dF(\alpha)\big/d\alpha = (1-2\alpha)[\gamma(1-\beta)(L_e + L_i) + \gamma R_i - C_i]$, letting $H(\gamma) = \gamma(1-\beta)(L_e + L_i) + \gamma R_i - C_i$.

When $\gamma = C_i\big/[(1-\beta)(L_e + L_i) + R_i] = \gamma *, H(\gamma) = 0$. Here, $dF(\alpha)\big/d\alpha \equiv 0$. This suggests that the status is ESP, regardless of the value α takes during the interval, and the strategy of investors does not change over time.

When $\gamma \neq C_i\big/[(1-\beta)(L_e + L_i) + R_i]$, if $F(\alpha) = 0$, then $\alpha = 0$ and $\alpha = 1$ are two ESPs. As $\partial H(\gamma)\big/\partial\gamma = (1-\beta)(L_e + L_i) + \gamma R_i > 0$, $H(\gamma)$ increases with γ.

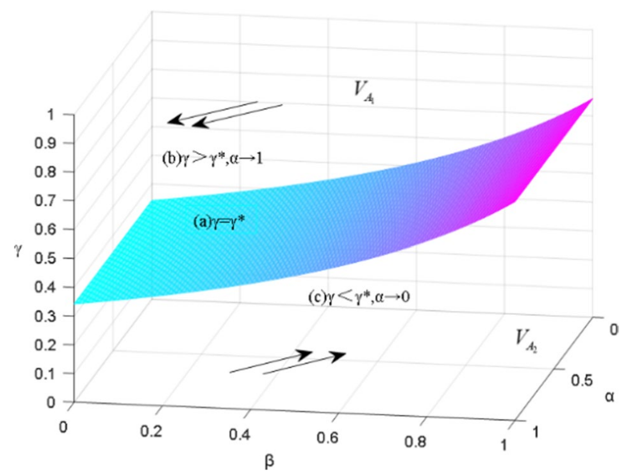

Fig. 3 Phase diagram of investors' strategy selection

(i) $\gamma* < \gamma < 1$, $H(\gamma) > 0$, $dF(\alpha)/d\alpha\big|_{\alpha=1} < 0$. Thus, $\alpha = 1$ is the ESP, suggesting that when the probability of regulatory authorities choosing the active supervision strategy is larger than a certain degree and continues to increase, the strategic choice of investors will be the feedback strategy.

(ii) $0 < \gamma < \gamma*$, $H(\gamma) < 0$, $dF(\alpha)/d\alpha\big|_{\alpha=0} < 0$; therefore, $\alpha = 0$ is ESP, and in such a case, investors' strategy choice is the non-feedback strategy. This indicates that when the probability of regulatory authorities choosing an active supervision strategy diminishes, investors will eventually choose the non-feedback strategy. The phase diagram of investors' strategy selection is depicted in Fig. 3.

From Fig. 3, the probability of investors choosing the feedback strategy is V_{A_1}, and the probability of investors choosing the non-feedback strategy is V_{A_2}, which can be calculated as follows:

$$V_{A_2} = \int_0^1 d\alpha \int_0^1 \frac{C_i}{(1-\beta)(L_e+L_i)+R_i} d\beta = \frac{C_i}{L_e+L_i} \ln\left(1+\frac{L_e+L_i}{R_i}\right) \tag{5}$$

$$V_{A_1} = 1 - V_{A_2} = 1 - \frac{C_i}{L_e+L_i} \ln\left(1+\frac{L_e+L_i}{R_i}\right) \tag{6}$$

Proposition 1. *The probability of investors choosing the feedback strategy is positively associated with the economic incentive gained from regulatory authorities* (R_i)*, the compensation from enterprises* (L_e)*, and the loss caused by greenwashing projects* (L_i) *and is negatively associated with feedback costs* (C_i).

Proof Based on the formula V_{A_1}, the partial derivative of each factor can be obtained.

$$\partial V_{A_1}/\partial R_i = \frac{C_i}{R_i(L_e+L_i+R_i)} > 0,\ \partial V_{A_1}/\partial L_e = \frac{C_m\left[(L_e+L_i+R_i)\ln\left(1+\frac{L_e+L_i}{R_i}\right)-(L_e+L_i)\right]}{(L_e+L_i)^2(L_e+L_i+R_i)} > 0,$$

$$\partial V_{A_1} \big/ \partial C_i = -\frac{\ln\left(1+\frac{L_e+L_i}{R_i}\right)}{L_e+L_i} < 0.$$

From Proposition 1, it can be concluded that the decision-making behaviors of investors are mainly based on the costs and benefits of feedback. The greater the loss of investors from greenwashing projects, the more likely they are to choose feedback. In addition, increasing the greenwashing compensation and economic reward to investors can effectively promote the enthusiasm of investor participation. Reducing the cost of feedback also helps to increase the motivation of investors. This indicates that regulatory authorities need to guide investors through policies. For investors, external intervention has an indirect influence on choosing the feedback strategy or not.

Proposition 2. *The high probability of regulatory authorities' active supervision and the probability of enterprises' greenwashing projects can effectively increase the probability of investors choosing the feedback strategy.*

Proof From the ESP analysis of investors, when $\gamma > \gamma*$, $\beta < 1 - \frac{C_i - \gamma R_i}{\gamma(L_e+L_i)} = \beta*$; thus, $H(\gamma) > 0$ and $dF(\alpha)\big/d\alpha\big|_{\alpha=1} < 0$, indicating that $\alpha = 1$ is the ESP of investors. Therefore, as γ increases and β decreases, $\alpha = 1$ is achieved, which indicates that feedback is a stable strategy for investors.

Proposition 2 indicates that when regulatory authorities increase the probability of active supervision, more investors will be willing to engage in feedback on greenwashing projects. As investors believe that active supervision by regulatory authorities can protect their rights, they will choose to give feedback on the quality of green projects. Moreover, when the GWBs of enterprises are widespread, it will have a general impact on investors, which can boost investors' participation in feedback.

(2) Stability analysis of enterprises' strategy

Similar to the investors, the expected benefit of enterprises' green project strategy is E_{21}; the benefit of enterprises selecting a greenwashing project strategy is E_{22}; and the average benefit of enterprises is $\overline{E_2}$.

$$\begin{aligned} E_{21} =& \alpha\gamma\left(V_e + R_e - \frac{1}{2}cg_1^2\right) + \gamma(1-\alpha)\left(V_e - \frac{1}{2}cg_1^2\right) \\ &+ \alpha(1-\gamma)\left(V_e + R_e - \frac{1}{2}cg_1^2\right) \\ &+ (1-\alpha)(1-\gamma)\left(V_e - \frac{1}{2}cg_1^2\right) \end{aligned} \tag{7}$$

$$E_{22} = \alpha\gamma(V_e - L_e - F_e) + \alpha(1-\gamma)V_e + \gamma(1-\alpha)(V_e - F_e) + (1-\alpha)(1-\gamma)V_e \tag{8}$$

$$\overline{E_2} = \beta E_{21} + (1-\beta)E_{22} = -\gamma(1-\beta)(\alpha L_e + F_e) + \alpha\beta R_e - \frac{1}{2}\beta c g_1^2 + V_e \tag{9}$$

The replication dynamic equation of enterprises is $F(\beta)$:

$$F(\beta) = d\beta\big/dt = \beta\left(E_{21} - \overline{E_2}\right) = \beta(1-\beta)\left(\alpha R_e - \frac{1}{2}cg_1^2 + \gamma F_e + \alpha\gamma L_e\right).$$

The probability of enterprises choosing green projects is ESP, when $F(\beta) = 0$ and $dF(\beta)\big/d\beta < 0$ are satisfied, where $dF(\beta)\big/d\beta = (1-2\beta)\left(\alpha R_e - \frac{1}{2}cg_1^2 + \gamma F_e + \alpha\gamma L_e\right)$, letting $J(\gamma) = \alpha R_e - \frac{1}{2}cg_1^2 + \gamma F_e + \alpha\gamma L_e$.

Because $\partial J(\gamma)\big/\partial\gamma = F_e + \alpha L_e > 0$, γ is positively associated with $J(\gamma)$, if $\gamma = \left(\frac{1}{2}cg_1^2 - \alpha R_e\right)\big/(F_e + \alpha L_e) = \gamma^{**}$, $J(\gamma) = 0$, $dF(\beta)\big/d\beta \equiv 0$. γ is the ESP in any value during the interval, and an enterprise's status will not change over time.

(i) When $\gamma^{**} < \gamma < 1$, $J(\gamma) > 0$, here $dF(\beta)\big/d\beta\big|_{\beta=1} < 0$, and $\beta = 1$ is the ESP, which means that an enterprise's green project strategy can reach a stable state.

(ii) When $0 < \gamma < \gamma^{**}$, $J(\gamma) < 0$, and $dF(\beta)\big/d\beta\big|_{\beta=0} < 0$; thus, $\beta = 0$ is the ESP of enterprises, suggesting that when the probability of regulatory authorities choosing an active supervision strategy is smaller than a certain degree and continues to decrease, the probability that enterprises are involved in a greenwashing project strategy increases. The phase diagram of enterprise strategy selection is depicted in Fig. 4.

Referring to Fig. 4, V_{B_1} represents the probability that enterprises will choose a green project strategy, while V_{B_2} represents the probability of the greenwashing project strategy.

$$V_{B_2} = \int_0^1 d\beta \int_0^1 \frac{\frac{1}{2}cg_1^2 - \alpha R_e}{F_e + \alpha L_e} d\alpha = -\frac{R_e}{L_e} + \frac{1}{2L_e^2} \ln\left(1 + \frac{L_e}{F_e}\right) \tag{10}$$

$$V_{B_1} = 1 - V_{B_2} = 1 + \frac{R_e}{L_e} - \frac{1}{2L_e^2} \ln\left(1 + \frac{L_e}{F_e}\right) \tag{11}$$

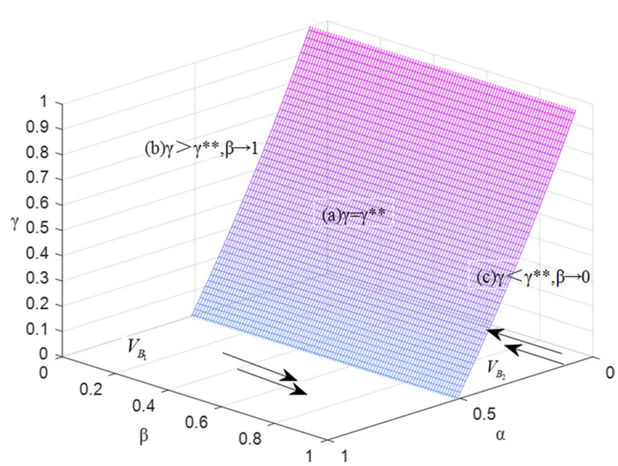

Fig. 4 Phase diagram of enterprise' strategy selection

Proposition 3 *The probability of enterprises investing in green projects is positively associated with the reputational benefits obtained by investor feedback R_e, the compensation given to investors L_e, and the punishment from regulatory authorities for investing in greenwashing projects F_e.*

Proof The first partial derivative of each factor of V_{B_1} can be obtained as follows:

$$\partial V_{B_1} \big/ \partial L_e = \frac{\ln\left(\frac{L_e}{F_e}+1\right)}{L_e^3} - \frac{R_e}{L_e^2} - \frac{1}{2L_e^2(L_e+F_e)} > 0,\ \partial V_{B_1} \big/ \partial F_e = \frac{1}{2L_eF_e(L_e+F_e)} > 0,\ \partial V_{B_1} \big/ \partial R_e = \frac{1}{L_e} > 0.$$

Proposition 3 reveals that as enterprises pursue their interests, the violation cost of greenwashing enterprises increases and the probability of GWBs decreases. On the one hand, enhancing the compensation to investors will put pressure on enterprises, reducing the probability of GWBs. On the other hand, a penalty can also have a deterrent effect. Based on this, regulatory authorities will generally strengthen supervision. In addition, to improve the word-of-mouth effect with the help of the media, adopting green projects can generate more reputation income for enterprises.

Proposition 4. *In the evolution process, the probability of enterprises taking on green projects increases with the probability of active regulatory authorities' supervision and the probability of investor feedback.*

Proof According to the stability analysis of enterprise strategies, when $\gamma > \gamma**$, $\alpha > \frac{\frac{1}{2}cg_1^2-\gamma F_e}{R_e+\gamma L_e} = \alpha*$; thus $J(\gamma) > 0$,$dF(\beta)\big/d\beta\big|_{\beta=1} < 0$, and $\beta = 1$ is the ESP. Therefore, with an increase in γ and a decrease in α, the evolutionary stability strategy of enterprises will tend toward $\beta = 1$ (green projects).

Proposition 4 posits that increases in the probability of regulatory authorities' active supervision and in the probability of investor feedback will encourage enterprises to adopt green projects. The active involvement of regulatory authorities and investors increases the cost and difficulty of GWBs. This increases the GWBs risk of enterprises, which will be conducive to preventing GWBs.

(3) Stability analysis of regulatory authorities' strategy

Similarly, for regulatory authorities, E_{31} represents the expected benefit of the active supervision strategy; E_{32} represents the expected benefit of the passive supervision strategy; and $\overline{E_3}$ is the average expected benefit.

$$E_{31} = \alpha\beta(R_r - C_r - R_i)+\alpha(1-\beta)(F_e + R_r - C_r - R_i)+\beta(1-\alpha)(-C_r)+(1-\alpha)(1-\beta)(F_e - C_r) \tag{12}$$

$$E_{32} = \alpha(1-\beta)(-L_r - L_s) + (1-\alpha)(1-\beta)(-L_s) \tag{13}$$

$$\overline{E_3} = \gamma E_{31} + (1-\gamma)E_{32} = (1-\beta)[\gamma F_e - (1-\gamma)(L_s + \alpha L_r)] + \alpha\gamma R_r - \alpha\gamma R_i - \gamma C_r \tag{14}$$

The replication dynamic equation of regulatory authorities $F(\gamma)$ is

$$F(\gamma) = d\gamma / dt = \gamma\left(E_{31} - \overline{E_3}\right) = \gamma(1-\gamma)[(1-\beta)(F_e + \alpha L_r + L_s) + \alpha R_r - \alpha R_i - C_r].$$

The first derivative of γ and $G(\alpha)$ are as follows:

$$dF(\gamma) / d\gamma = (1 - 2\gamma)[(1-\beta)(F_e + \alpha L_r + L_s) + \alpha R_r - \alpha R_i - C_r],$$

where $G(\alpha) = (1-\beta)(F_e + \alpha L_r + L_s) + \alpha R_r - \alpha R_i - C_r$.

When both $F(\gamma) = 0$ and $dF(\gamma) / d(\gamma) < 0$ are satisfied, the probability of regulatory authorities choosing active supervision is stable.

Because $\partial G(\alpha) / \partial\alpha = (1-\beta)L_r + R_r - R_i > 0, G(\alpha)$ increases with α. If $\alpha = [C_r - (1-\beta)(F_e + L_s)] / [R_r - R_i + (1-\beta)L_r] = \alpha*$, $G(\alpha) = 0$, and $dF(\gamma) / d\gamma \equiv 0$, it suggests that any strategy implemented by regulatory authorities is stable, regardless of the value α takes during the interval.

(i) If $\alpha* < \alpha < 1, G(\alpha) > 0$, and $dF(\gamma) / d\gamma\big|_{\gamma=1} < 0$, then $\gamma = 1$ is the ESP of regulatory authorities. When the probability of investors choosing the feedback strategy is greater than a certain degree, the probability of the active supervision strategy increases, and eventually, the active supervision strategy achieves a stable state.

(ii) If $0 < \alpha < \alpha*$, $G(\alpha) < 0$, $dF(\gamma) / d\gamma\big|_{\gamma=0} < 0$, $\gamma = 0$ is the regulatory authorities' ESP. When the probability of investors choosing the feedback strategy is smaller than a certain degree and continues to decrease, the probability of regulatory authorities choosing to accept the active supervision strategy decreases, and eventually, regulatory authorities will choose the opposite strategy. The strategy-selection phase diagram of regulatory authorities is depicted in Fig. 5.

Similarly, the probability of regulatory authorities choosing active supervision is V_{C_1}, and the probability of passive supervision is V_{C_2}, which can be calculated as follows:

$$V_{C_2} = \int_0^1 d\gamma \int_0^1 \frac{C_r - (1-\beta)(F_e + L_s)}{R_r - R_i + (1-\beta)L_r} d\beta = -\frac{F_e + L_s}{L_r} + \frac{1}{L_r^2} \ln\left(1 - \frac{L_r}{R_i - R_r}\right) \tag{15}$$

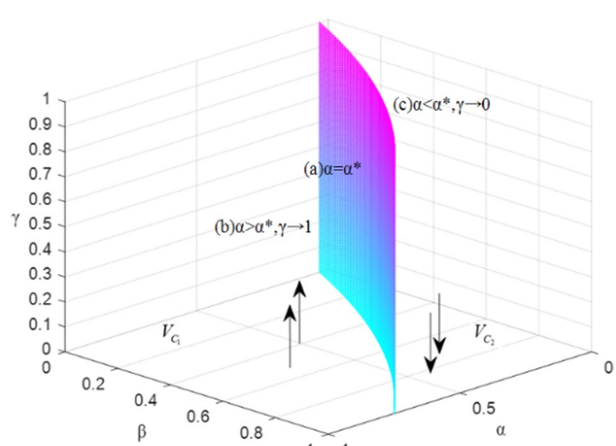

Fig. 5 Phase diagram of the regulatory authorities' strategy selection

$$V_{C_1} = 1 - V_{C_2} = 1 + \frac{F_e + L_s}{L_r} - \frac{1}{L_r^2} \ln\left(1 - \frac{L_r}{R_i - R_r}\right) \tag{16}$$

Proposition 5. *The probability of regulatory authorities choosing active regulation is positively associated with reputational loss L_r, reputational gain from investor feedback R_r, fines against greenwashing enterprises F_e, and social welfare losses L_s and is negatively associated with the feedback reward given to investors R_i.*

Proof Using V_{C_1}, the first partial derivative of each factor is obtained.

$$\partial V_{C_1} \big/ \partial L_r = \frac{2\ln\left(1 + \frac{L_r}{R_r - R_i}\right)}{L_r^3} - \frac{F_e + L_s}{L_r^2} - \frac{1}{L_r^2(L_r - R_i + R_r)} > 0,$$

$$\partial V_{C_1} \Big/ \partial R_r = \frac{1}{L_r(R_r - R_i)(L_r + R_r - R_i)} > 0,$$

$$\partial V_{C_1} \Big/ \partial F_e = \frac{1}{L_r} > 0,\ \partial V_{C_1} \Big/ \partial L_s = \frac{1}{L_r} > 0,\ \partial V_{C_1} \Big/ \partial R_i = \frac{-1}{L_r(R_r - R_i)(L_r + R_r - R_i)} < 0.$$

Proposition 5 indicates that the higher the penalty imposed on greenwashing enterprises, the lower the supervision cost. Regulatory authorities are more willing to take the initiative to conduct effective regulation. The greater the loss of social welfare caused by greenwashing, the more active regulatory authorities will be promoted. However, the reward to investors will incentivize them to participate in the development of GFPs, thus reducing the task of regulatory authorities. In addition, increasing the reputation loss of passive supervision will put pressure on regulatory authorities, and it also encourages them to choose active supervision.

Proposition 6. *The probability of regulatory authorities choosing active supervision increases with the probability of investor feedback and the probability of enterprises engaging in greenwashing projects.*

Proof According to the stability analysis of the strategy of regulatory authorities, when $\alpha > \alpha*$, $\beta < 1 - \frac{\alpha R_i + C_r - \alpha R_r}{F_e + \alpha L_r + L_s} = \beta*$. Here, $G(\alpha) > 0$ and $dF(\gamma) \big/ d\gamma \big|_{\gamma=1} < 0$, so $\gamma = 1$ is the ESP of regulatory authorities. Therefore, as α increases and β gradually decreases, the more regulatory authorities tend to choose an active supervision strategy ($\gamma = 1$).

Proposition 6 illustrates that to develop GFPs and satisfy investors, the participation of investors can promote active supervision by regulatory authorities. When the GWBs phenomenon of enterprises is very prominent, the supervision of regulatory authorities will inevitably be strengthened.

Based on the analysis and calculation of the above proposition, the influencing factors of the equilibrium probability of investors, enterprises, and regulatory authorities are summarized in Table 4.

Table 4 Increasing the equilibrium probability with model parameters

Investors equilibrium probability	α	R_i L_e L_i C_i β γ ↑ ↑ ↑ ↓ ↓ ↑
Enterprises equilibrium probability	β	R_e L_e F_e α γ ↑ ↑ ↑ ↑ ↑
Regulatory authorities equilibrium probability	γ	R_r L_r F_e L_s R_i α β ↑ ↑ ↑ ↑ ↓ ↑ ↓

↑: Increasing, ↓: Decreasing

Stability analysis of the tripartite evolutionary game

The evolutionary stability of investors, enterprises, and regulatory authorities can be described using tripartite replicative dynamic equations (Yang et al. 2020). The three-dimensional dynamic system of investors, enterprises, and regulatory authorities can be obtained as follows.

$$\begin{cases} F(\alpha) = \dfrac{d\alpha}{dt} = \alpha(1-\alpha)[\gamma(1-\beta)(L_e+L_i)+\gamma R_i - C_i] \\ F(\beta) = \dfrac{d\beta}{dt} = \beta(1-\beta)(\alpha R_e - \dfrac{1}{2}cg_1^2 + \gamma F_e + \alpha\gamma L_e) \\ F(\gamma) = \dfrac{d\gamma}{dt} = \gamma(1-\gamma)[(1-\beta)(F_e+\alpha L_r+L_s)+\alpha(R_r-R_i)-C_r] \end{cases}$$

According to D. Frideman, evolutionary equilibrium points are only acceptable in a pure strategy of asymmetric evolutionary games and can be determined from the Jacobian matrix J (Cantner et al. 1999). Thus, only the stability of $E_1(0,0,0)$,$E_2(1,0,0)$, $E_3(0,1,0)$, $E_4(0,0,1)$, $E_5(1,1,0)$, $E_6(1,0,1)$, $E_7(0,1,1)$, and $E_8(1,1,1)$ need to be considered.

$$J = \begin{pmatrix} J_1 & J_2 & J_3 \\ J_4 & J_5 & J_6 \\ J_7 & J_8 & J_9 \end{pmatrix} = \begin{pmatrix} \partial F(\alpha)/\partial\alpha & \partial F(\alpha)/\partial\beta & \partial F(\alpha)/\partial\gamma \\ \partial F(\beta)/\partial\alpha & \partial F(\beta)/\partial\beta & \partial F(\beta)/\partial\gamma \\ \partial F(\gamma)/\partial\alpha & \partial F(\gamma)/\partial\beta & \partial F(\gamma)/\partial\gamma \end{pmatrix} =$$

$$\begin{pmatrix} (1-2\alpha)\left[\gamma(1-\beta)\left(L_e+L_i\right)+\gamma R_i - C_i\right] & -\alpha(1-\alpha)\gamma\left(L_e+L_i\right) & \alpha(1-\alpha)\left[(1-\beta)\left(L_e+L_i\right)+R_i\right] \\ \beta(1-\beta)(R_e+\gamma L_e) & (1-2\beta)\left(\alpha R_e - \frac{1}{2}cg_1^2 + \gamma F_e + \gamma\alpha L_e\right) & \beta(1-\beta)(F_e+\alpha L_e) \\ \gamma(1-\gamma)\left[(1-\beta)L_r + R_r - R_i\right] & -\gamma(1-\gamma)(F_e+\alpha L_r+L_s) & (1-2\gamma)\left[(1-\beta)(F_e+\alpha L_r+L_s)+\alpha\left(R_r-R_i\right)-C_r\right] \end{pmatrix}$$

According to the Lyapunov stability theory, an equilibrium point is substituted into the Jacobian matrix when and only when the three eigenvalues are less than zero and the equilibrium point is an evolutionarily stable strategy (ESS). The eigenvalues of the Jacobian matrix are presented in Table 5.

According to Table 5, when the corresponding asymptotic stability conditions are satisfied, the eigenvalues of the Jacobian matrix are all negative; therefore, there are four possible ESSs of the system, i.e., $E_1(0,0,0)$, $E_4(0,0,1)$, $E_6(1,0,1)$, and $E_8(1,1,1)$. The conditions for achieving different ESSs will be investigated further in Section "Numerical simulation".

Table 5 Eigenvalues of the Jacobian matrix

Equilibrium points	Eigenvalue λ_1,λ_2,λ_3	Sign	Stability	Stability conditions
$E_1(0,0,0)$	$-C_i, -\frac{1}{2}cg_1^2, F_e + L_s - C_r$	(–, –, *)	ESS	$F_e + L_s < C_r$
$E_2(1,0,0)$	$C_i, R_e - \frac{1}{2}cg_1^2, F_e + L_r + L_s + R_r - R_i - C_r$	(+, *, *)	Unstable	–
$E_3(0,1,0)$	$-C_i, \frac{1}{2}cg_1^2, -C_r$	(–, +, –)	Unstable	–
$E_4(0,0,1)$	$L_e + L_i + R_i - C_i, F_e - \frac{1}{2}cg_1^2, C_r - F_e - L_s$	(*, *, *)	ESS	$L_e + L_i + R_i < C_i$ $F_e < \frac{1}{2}cg_1^2$ $C_r < F_e + L_s$
$E_5(1,1,0)$	$C_i, -R_e + \frac{1}{2}cg_1^2, R_r - R_i - C_r$	(+, *, *)	Unstable	–
$E_6(1,0,1)$	$C_i - L_e - L_i - R_i, R_e + F_e + L_e - \frac{1}{2}cg_1^2,$ $R_i + C_r - F_e - L_r - L_s - R_r$	(*, *, *)	ESS	$C_i < L_e + L_i + R_i$ $R_e + F_e + L_e < \frac{1}{2}cg_1^2$ $R_i + C_r < F_e + L_r + L_s + R_r$
$E_7(0,1,1)$	$R_i - C_i, \frac{1}{2}cg_1^2 - F_e, C_r$	(*, *, +)	Unstable	–
$E_8(1,1,1)$	$C_i - R_i, \frac{1}{2}cg_1^2 - R_e - F_e - L_e, R_i + C_r - R_r$	(*, *, *)	ESS	$C_i < R_i$ $\frac{1}{2}cg_1^2 < R_e + F_e + L_e$ $R_i + C_r < R_r$

*Indicates uncertainty

Numerical simulation

Evolutionary trajectories of ESSs

Numerical simulation is utilized to test the results. The initially designed numerical values follow the propositions of each ESS in Section "Stability analysis of the tripartite evolutionary game". In October 2022, we interviewed some GFP parties, including five government officials, eight enterprise managers, and ten investors in Shandong Province. We also draw on the relevant literature on the application of evolutionary game simulation, revealing that the setting of parameter values should both satisfy the value range and meet the condition of equilibrium solution (Guo et al. 2022; Zhang and Kong 2022). Based on this, the initial parameter values are set (see Table 6), and the simulation is implemented using MATLAB 2020b.

Scenario I. When $F_e + L_s < C_r$ is satisfied, it suggests that when the sum of the fine and social welfare loss of greenwashing projects is smaller than the supervision cost of regulatory authorities, $E_1(0,0,0)$ is the ESS, as depicted in Fig. 6 (a_1). Assuming that the probability of the initial choice of all three parties is 0.5, the evolutionary trajectory in the game is as depicted in Fig. 6 (a_2). Thus, non-feedback, greenwashing projects, and passive supervision is the ESS.

Table 6 Numerical values for different parameters of ESSs

Parameters	$E_1(0,0,0)$	$E_4(0,0,1)$	$E_6(1,0,1)$	$E_8(1,1,1)$	Assignment basis
L_e	0.3	0.1	0.1	0.2	Interview
L_i	0.2	–	–	0.1	Literature
R_i	0.1	–	–	0.2	Literature
C_i	0.3	0.6	0.15	0.1	Interview
R_e	0.6	0.3	0.3	0.7	Interview
c	0.2	–	–	-	Literature
g_1	2	3	3	3	Interview
F_e	0.1	0.2	0.2	0.3	Interview
L_r	0.3	–	–	0.2	Interview
C_r	0.5	0.4	0.4	0.2	Literature
L_s	0.1	0.3	0.2	0.3	Literature
R_r	0.4	0.3	-	0.5	Literature

"–" means that the assignment in this scenario is consistent with $E_1(0,0,0)$

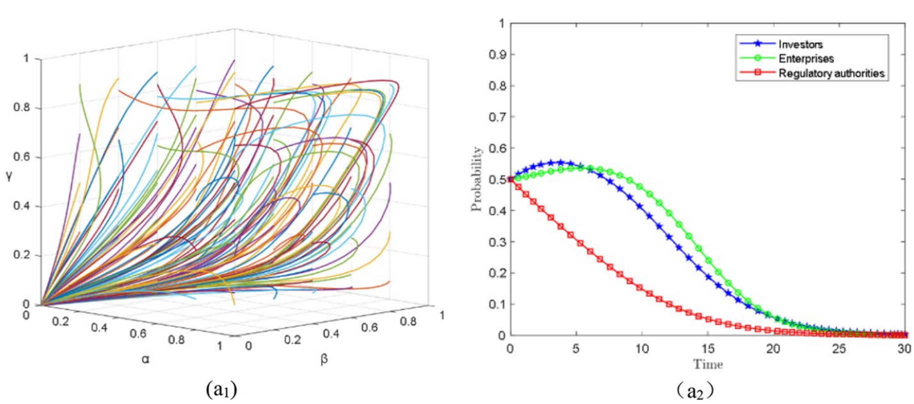

Fig. 6 Evolution trajectory of $E_1(0,0,0)$

In this scenario, regulatory authorities and investors will not have the incentive to supervise enterprises. The main reason for this result is that the payoff for them is lower than the cost. Finally, regulatory authorities will choose passive supervision, and investors will select non-feedback. In this scenario, the GWBs of enterprises occur frequently.

Scenario II. When the conditions $L_e + L_i + R_i < C_i$, $F_e < \frac{1}{2}cg_1^2$, and $C_r < F_e + L_s$ are satisfied, it suggests that (i) the feedback cost of investors exceeds the sum of the compensation given by greenwashing enterprises, the loss of greenwashing projects, and the feedback reward; (ii) the penalty imposed on greenwashing enterprises is less than the cost of green projects; and (iii) the sum of the penalty and the social welfare loss caused by GWBs is greater than the supervision cost. $E_4(0,0,1)$ is an ESS. Figure 7 (a_1) depicts the strategy of the evolution. The evolutionary trajectory in the game is demonstrated in Fig. 7 (a_2).

Situation II is the initial developmental stage of GFPs. The governance of GWBs belongs to the mandatory mode. Only regulatory authorities use administrative licensing, inspection, and standards as a deterrent to enterprises. However, due to the limited constraints on enterprises and as the enthusiasm of investors to participate in supervision is not high, the GWBs of enterprises cannot be effectively combated.

Scenario III. The conditions necessary for $E_6(1,0,1)$ to achieve ESS can be expressed as $C_i < L_e + L_i + R_i$, $R_e + F_e + L_e < \frac{1}{2}cg_1^2$ and $R_i + C_r < F_e + L_r + L_s + R_r$. This suggests that i) the gain of investor feedback (the sum of the compensation and the feedback reward) is greater than the cost; ii) the sum of rewards, penalties, and compensations given to investors by enterprises is less than the cost of green projects; and iii) the sum of the feedback reward and supervision cost is less than the benefits offered by regulatory authorities (the sum of penalty, social welfare loss, and reputation gain). The ESS and the evolutionary trajectory are depicted in Fig. 8 (a_1) and (a_2), respectively.

Scenario III belongs to the rapid developmental stages of GFPs, and the governance of GWBs is in the incentive mode. Even if regulatory authorities carry out active supervision and investors begin to participate in the feedback of GFPs, due to the imperfect regulatory system, enterprises still carry out greenwashing projects. It is also difficult to prevent enterprises from engaging in GWBs.

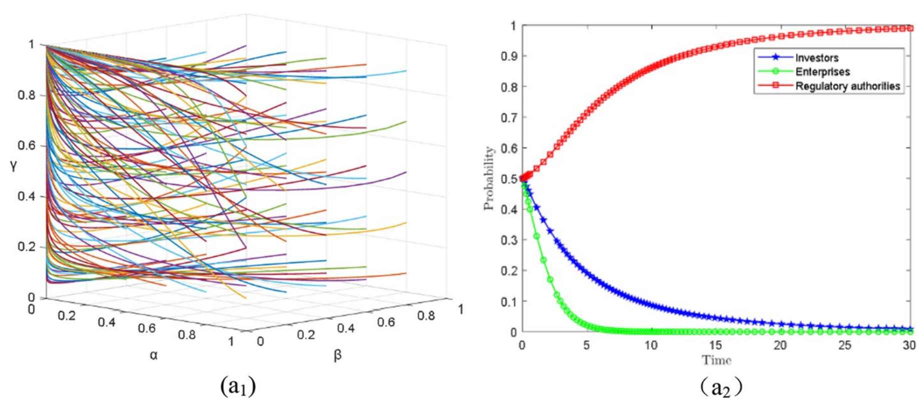

Fig. 7 Evolution trajectory of $E_4(0,0,1)$

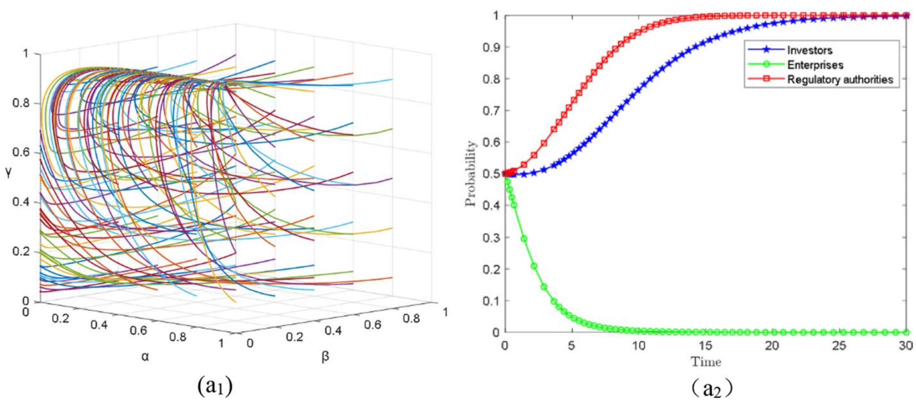

Fig. 8 Evolution trajectory of $E_6(1, 0, 1)$

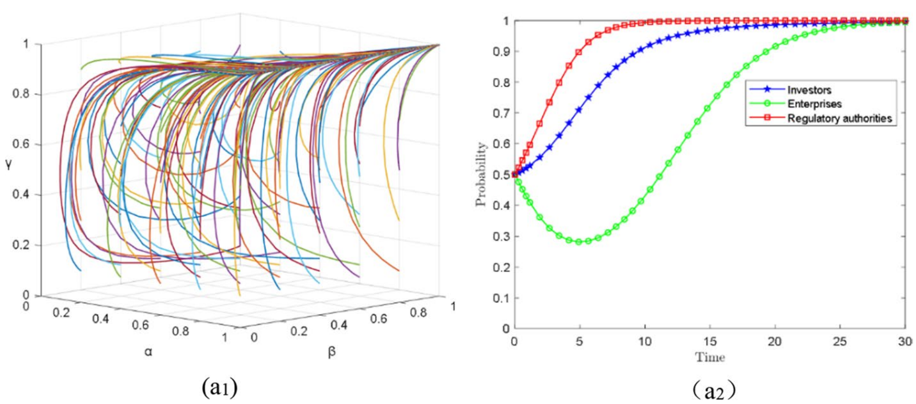

Fig. 9 Evolution trajectory of $E_8(1, 1, 1)$

Scenario IV. The conditions for $E_8(1, 1, 1)$ to be an ESS are when $C_i < R_i$, $\frac{1}{2}cg_1^2 < R_e + F_e + L_e$, and $R_i + C_r < R_r$ are satisfied. This suggests that (i) the cost of investor feedback is less than the reward; (ii) the sum of the economic incentives, penalty, and compensation given to investors is greater than the cost of green projects; and (iii) the sum of the reward to investors and the supervision cost is less than the reputational benefit obtained under active supervision. The evolutionary trajectory is depicted in Fig. 9 (a_1) and (a_2).

At this stage, when the scale of GFPs is approaching stability, the mature stage is the collaboration mode. The regulatory authorities integrate various resources, and a comprehensive governance structure is built, modernizing the GFP governance system. This stage is the optimal equilibrium point, and the strategies of the three players in the game are feedback, positive supervision, and green projects.

Based on stable equilibrium strategies in the game, under different developmental states of GFPs, the corresponding governance mechanism of GWBs is proposed (see Fig. 10).

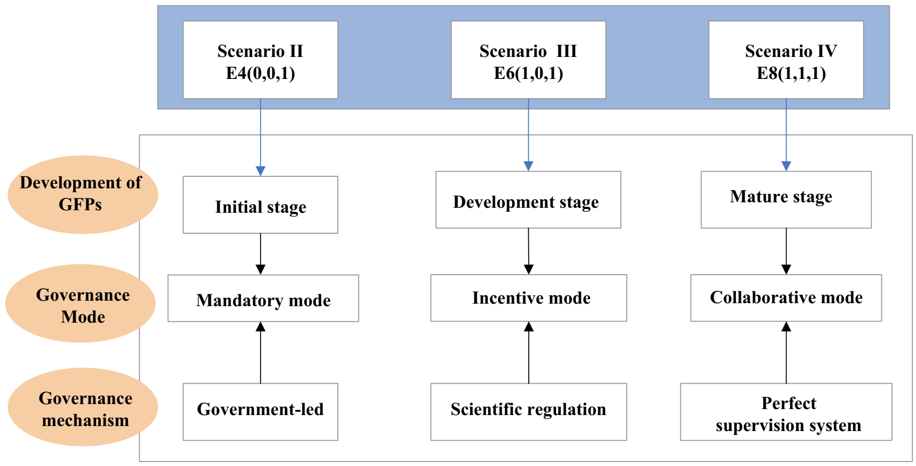

Fig. 10 Different governance mechanisms of GWBs in GFPs

Impacts of critical factors on evolutionary results

To identify the critical factors affecting regulatory authorities, investors, and enterprises, we mainly selected the influencing factors in the following ways. On the one hand, because $E_8(1,1,1)$ is the optimal choice to govern the GWBs of GFPs, the parameters in this ESS will be selected. On the other hand, from the perspective of GWBs governance, the key influencing factors are investigated further.

(1) Reputational Returns of Enterprises R_e

With an increase in R_e, the ESS of the game changes from $E_6(1,0,1)$ to $E_8(1,1,1)$. This corresponds to a change in enterprise strategy, i.e., the strategy shifts from greenwashing projects to green projects (see Fig. 11). Moreover, the larger R_e is, the shorter the time required for an enterprise to achieve the implementation of green projects.

Therefore, increasing the public praise effect, enhancing the reputation, and improving the brand value of enterprises are conducive to encouraging enterprises to engage in green projects.

(2) Compensation to investors L_e

After an increase in the compensation for investors L_e, the evolution result of the system is not affected; however, it affects the time length and convergence speed of the evolution (see Fig. 12).

For enterprises, with an increase in the compensation given to investors, the time it takes to achieve investment in green projects decreases. Thus, an increase in the compensation for investors due to enterprises' green bleaching can accelerate the evolution speed of enterprises' choice of green projects, while for both investors and regulatory authorities, as L_e increases, it takes them a longer time to reach a stability strategy.

(3) Penalty for greenwashing projects F_e

From Fig. 13, we find that ESS changes from $E_6(1,0,1)$ to $E_8(1,1,1)$ as F_e increases. The larger F_e is, the shorter the time required for enterprises to achieve a stable strategy of green projects. For investors, along with an increase in F_e, the time needed to achieve the stability of investors choosing the feedback strategy gradually decreases, while the time for regulatory authorities to choose active supervision increases.

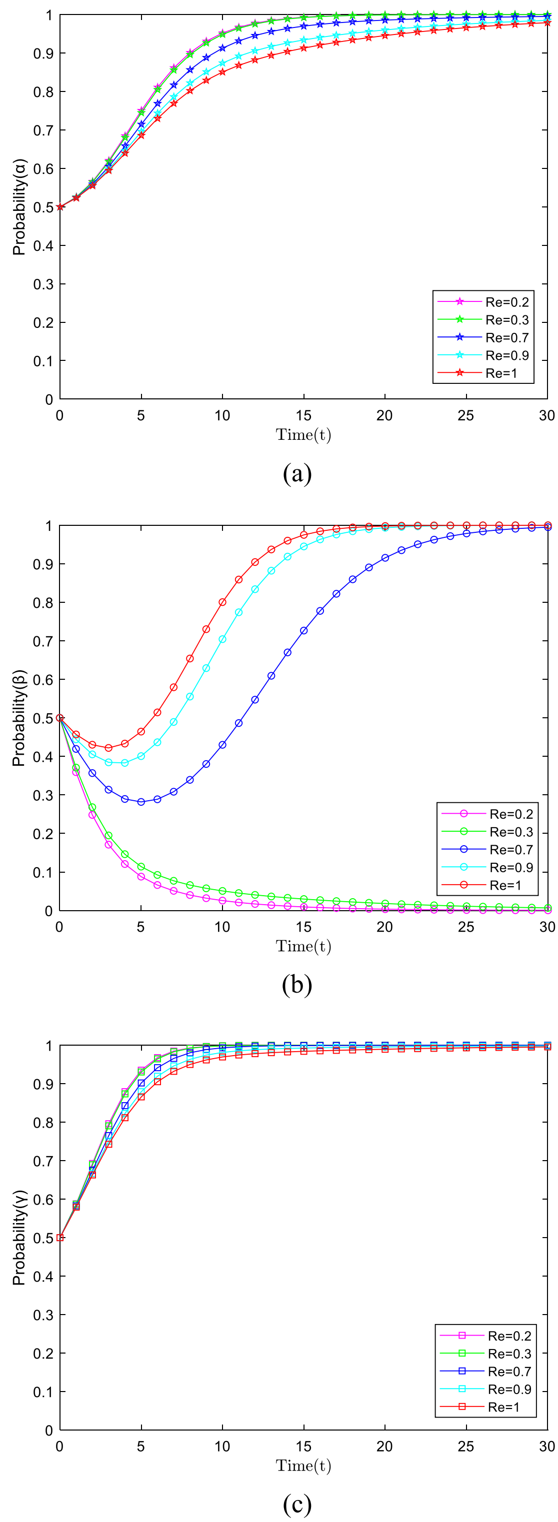

Fig. 11 Impact of reputational returns

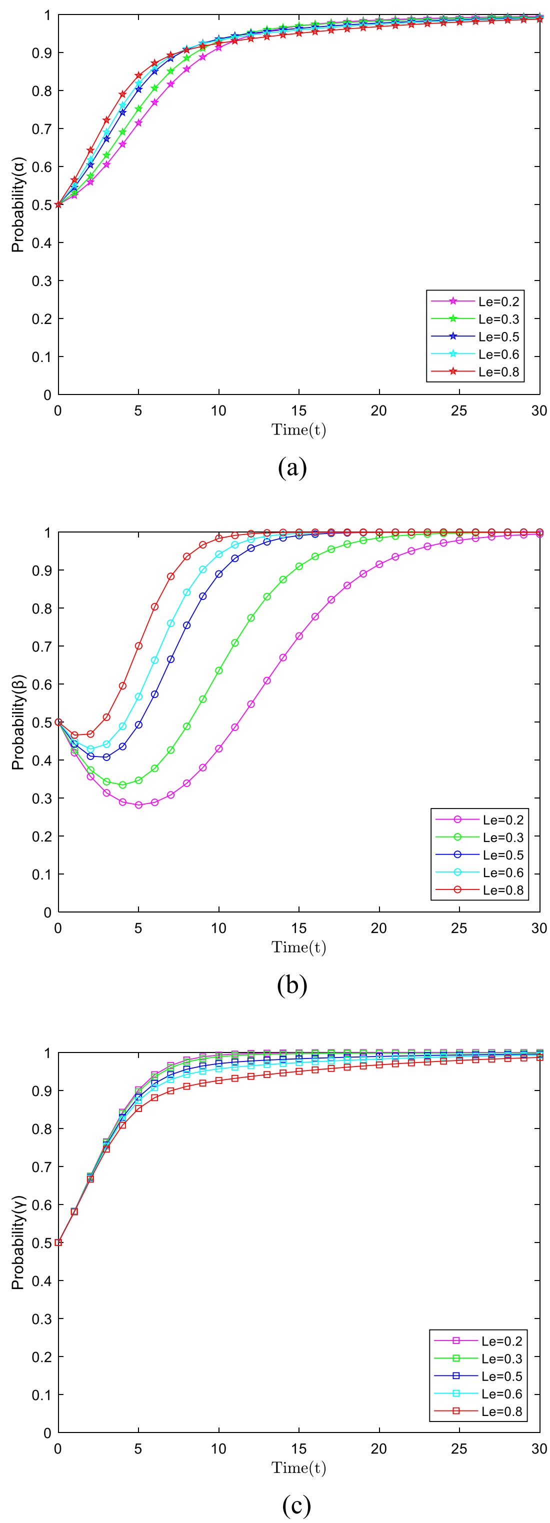

Fig. 12 Impact of compensation to investors

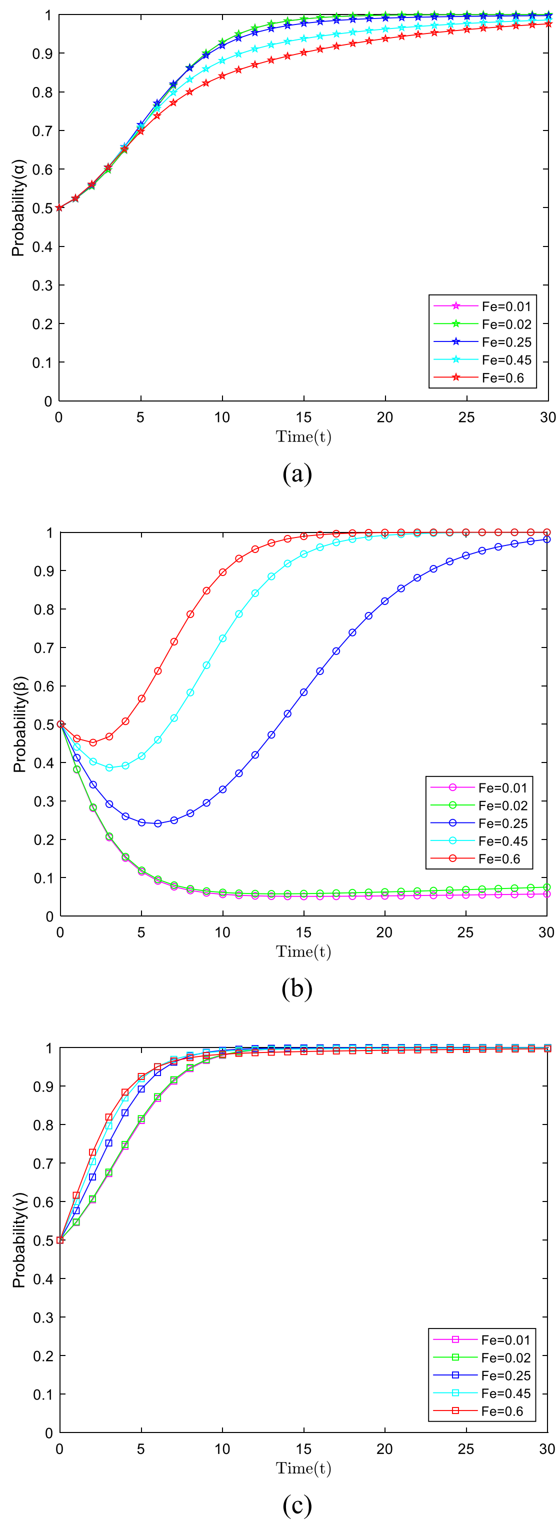

Fig. 13 Impact of penalty on greenwashing projects

Therefore, an increase in the fine on greenwashing enterprises can accelerate the evolution speed of enterprise investment in green projects. When more and more enterprises choose investment in green projects, the supervision of regulatory authorities naturally diminishes. Thus, imposing an appropriate punishment mechanism on enterprises for their GWBs is conducive to guaranteeing investment in green projects.

(4) Quality of green projects g_1

The ESS of the game evolves from $E_8(1,1,1)$ to $E_6(1,0,1)$ as g_1 increases (see Fig. 14). With an increase in g_1, the time needed for enterprises to achieve stability of a green project strategy increases. Thus, the high-quality standard of green projects is not conducive to the occurrence of GWBs.

The formulation of appropriate evaluation standards is the key to ensuring that enterprises promote green projects. Regulatory authorities should vigorously support enterprises and gradually improve the standards of green projects to reduce the implementation cost of such projects.

(5) Feedback cost C_i

The results of the impact of feedback costs on the evolutionary game are depicted in Fig. 15. The ESS of the game evolves from $E_8(1,1,1)$ to $E_4(0,0,1)$ as C_i increases. For investors and enterprises, in the case of $C_i \leq 0.25$, investors will choose feedback, and enterprises will choose green projects. However, when $C_i \geq 0.6$, investors are more likely to choose non-feedback, and enterprises will choose greenwashing projects.

This suggests that a decrease in the cost of feedback not only increases investor feedback but also encourages enterprises to choose green projects. Therefore, regulatory authorities should reduce or even exempt companies from the cost of identification and improve economic rewards to guide investor behavior, thus promoting the enthusiasm of investors toward the feedback strategy.

(6) Initial probability of tripartite game strategies

Figure 16 depicts that the initial probability of the three parties' strategy choices has a positive influence on the evolution path. When the probability selection of the initial strategies is 0.2, the ESP is $E_6(1,0,1)$. When the probability of the initial strategy choice is greater than 0.2, the ESP is $E_8(1,1,1)$, which indicates that a change in the initial strategy choice not only affects the evolution trajectory but also changes the final equilibrium result.

An increase in the initial probability of active supervision and feedback would effectively push enterprises to take on green projects. The stronger the initial willingness, the shorter the time it takes for enterprises to choose to invest in green projects. Therefore, in the initial stage, regulatory authorities should play a guiding role to increase the proportion of enterprises and investors participating in green projects.

Conclusions, policy recommendations, and limitations

This study analyzed the governance of enterprises' GWBs in GFPs from the stakeholder perspective. By discussing the relationships among regulatory authorities, investors, and enterprises in detail, the formation mechanism of GWBs was revealed. Then, drawing on the evolutionary game theory, a tripartite game model that includes regulatory authorities, enterprises, and investors was established. A stability equilibrium analysis of each player's strategy and the tripartite evolutionary game was

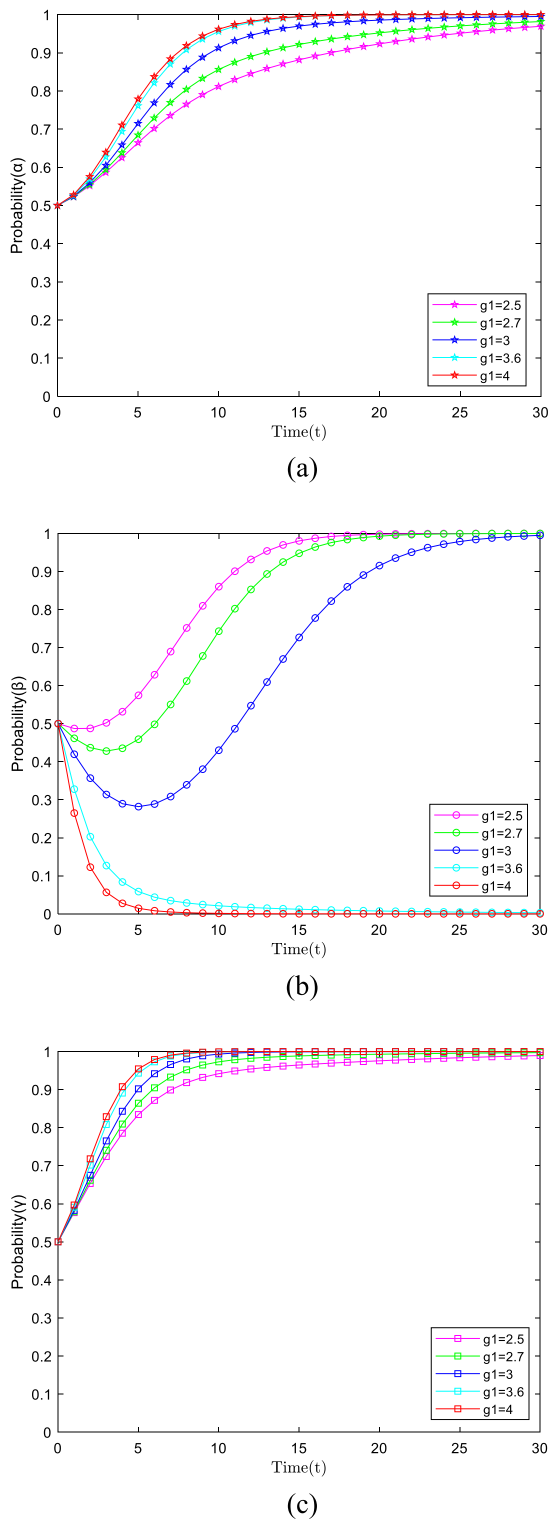

Fig. 14 Impact of the quality of green projects

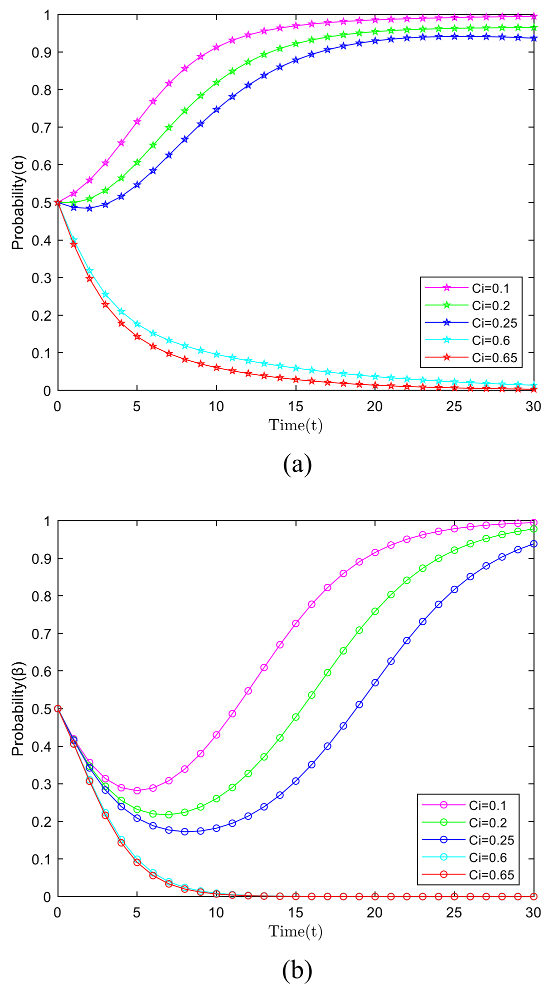

Fig. 15 Impact of the cost of feedback

conducted, revealing stakeholders' strategy-making behaviors in GFPs. Finally, we conducted a simulation to discuss the different influencing factors on the evolutionary results. The main findings are as follows.

First, the interdependence mechanism among the three game agents lead to mutual influence. Specifically, the larger the probability of regulatory authorities choosing active supervision and investors adopting feedback, the more enterprises are willing to carry out green projects. In summary, the strategy evolution paths of the game agents have a reliable degree of interdependence. The results also indicate that investor participation is a new way of conducting higher-intensity supervision and plays a positive role in controlling GWBs.

Second, there are four ESSs in the tripartite evolutionary game model, and their corresponding stable conditions were discerned. Based on the analysis of ESSs, three governance modes are proposed in the different development stages of GFPs. Among these modes, the collaboration mode is efficient and feasible, which would be useful for regulatory authorities to establish appropriate management measures to combat GWBs.

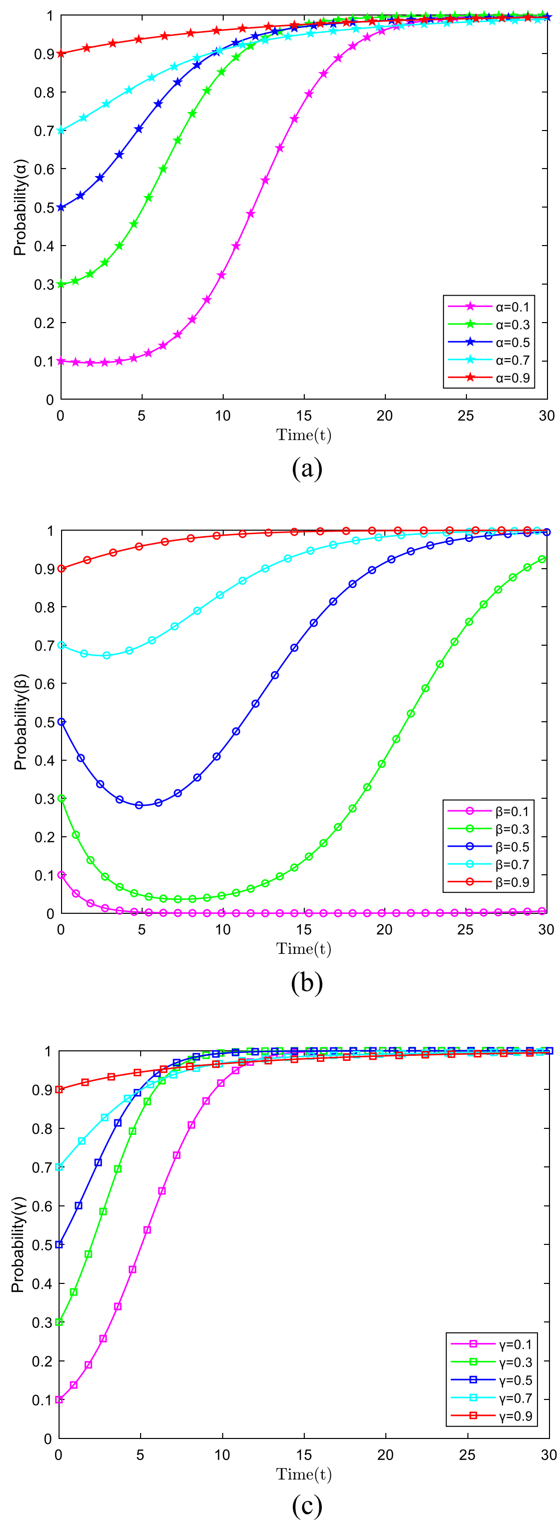

Fig. 16 Impact of the initial probability

Third, the impacts of key factors influencing the equilibrium results were identified. The critical factors include the feedback cost and compensation of investors, the initial probability of the tripartite game, the reputational benefits of enterprises, the penalties for greenwashing enterprises, and the quality of green projects. All of the above factors play a vital role in the evolutionary game results. Continuously adjusting and optimizing changes would speed up the game system to reach an ideal stable state.

Based on the research conclusions drawn above, several management implications are proposed to advance the effective prevention of GWBs.

1. Strengthen the mutual collaboration governance mechanism. The cooperative supervision of GFPs can actively improve efficiency. Moreover, when the initial willingness for regulatory authorities, enterprises, and investors to cooperate is high, it is conducive to resolving the challenge of GWB governance in the long run. Therefore, with the increasing scale of GFPs, regulatory authorities can change their governance mode for GFPs from mandatory intervention to collaborative regulation. A conducive environment should be created to encourage the enthusiasm of enterprises and investors to join in the regulation of GFPs. Further, regulatory authorities should play a leading role by providing incentives for GFPs and guaranteeing green infrastructure construction to promote enterprises' green behavior. Moreover, a sharing mechanism of financial risks with investors can be established by regulatory authorities; this can assist investors in making more informed and better GFPs investments.
2. Establish multiple channels to reduce the cost of participation. The government should make full use of modern financial technology such as the big data supervision platform to provide convenient and efficient channels for investors to reduce feedback costs. Thus, an intelligent information distribution platform can be developed, which extracts relevant data from multiple sources including enterprise reports, government policies, and investor evaluation. Constructing a stakeholder linkage digitalization platform for information disclosure can allow investors to evaluate enterprises' reputations online, which would not only improve the reputational spillover effect of enterprises' green projects but also provide a basis for investors to make feedback decisions.
3. Establish a strong dynamic reward and penalty mechanism. Enterprises are sensitive to regulatory authorities' rewards and penalties. Therefore, economic incentives can effectively promote the quality of GFPs over time, such as rewards for investing in green projects that contribute to convincing enterprises to choose green project strategies. Regulatory authorities can establish a comprehensive environmental performance evaluation system that includes indicators of GFPs, which would encourage enterprises to actively ensure the quality of GFPs. Moreover, disclosing rewards for effective feedback from investors through the web and new media would encourage them to supervise GFPs actively. Moreover, the punishment for GWBs strengthens enterprise self-discipline; thus, regulatory authorities should perfect the punishment mechanism by formulating laws and policies in GFPs to punish fraudulent behavior to curb GWBs.
4. Set appropriate standards for green projects. It is interesting to note that setting standards for green projects too high does not effectively prevent GWBs. In par-

ticular, in the early stages, the standards for GFPs should not be overly high as it is likely to affect the enthusiasm of enterprises. Intelligent and dynamic standards analysis models can be developed by regulatory authorities to identify key factors in the examination of the respective development stage of GFPs, and the quantity and quality of GFPs can also be accurately analyzed. Therefore, regulatory authorities can effectively choose a medium level of standards for green projects.

This study analyzes the GWBs of GFPs by constructing a tripartite evolutionary game model. Compared with the existing literature, it discusses the formation mechanisms of GWBs in GFPs in detail. The conclusions can provide decision support for stakeholders to adjust strategies. In particular, under different developmental states of GFPs, we have identified different governance mechanisms. This finding can help regulatory authorities to improve incentive measures. However, this study only examined the main factors using simulation values. In future studies, we will use the game model to conduct an empirical analysis based on real data. Furthermore, as the game participants in GWBs are homogeneous, an evolutionary game model involving heterogeneous participation will be the next research direction.

Abbreviations

GWBs	Greenwashing behaviors
GFPs	Green finance products
ESP	Evolutionary stable point
ESS	Evolutionarily stable strategy
ESG	Environmental, social, and governance

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Author contributions
CL: Conceptualization, Writing-Original Draft, Writing-Reviewing and Editing. WL: Writing- Original Draft, Software, Calculation. LC: Supervision, Writing-Reviewing, Data analysis. QJ: Supervision, Writing-Reviewing and Editing.

Availability of data and materials
The data that support the findings of this study are available from the authors upon reasonable request.

Declarations

Competing interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The corresponding author Qiang Ji also declares that as a guest editor of another VSI, he has no competing interests in this paper.

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