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ORIGINAL - OR MODELING/CASE STUDY

Unmasking greenwashing in ESG disclosure: insights from evolutionary game analysis

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Abstract
Environmental, Social, and Governance (ESG) disclosure is acknowledged as a compelling initiative to facilitate sustainable business practices. However, greenwashing undermines the credibility of this initiative, presenting a decision dilemma for stakeholders. Involving principal stakeholders (enterprises, investors, rating agencies) in ESG disclosure, this study conducts an evolutionary game analysis to explore the strategic evolution mechanisms. The equilibrium results suggest the potential market dilemma stemming from deceptive enterprises and unreliable rating agencies. Meanwhile, the system can converge to an ideal state without greenwashing. Reaching this state necessitates a market-based approach combined with government regulations, such as the ongoing monitoring of rating agencies to provide truthful and stringent ESG evaluation. Additionally, mandatory enterprise ESG disclosure is a robust measure to curb greenwashing. Investment-returns-based solutions can be considered for investors to augment the rigorous ESG ratings. Managers should understand the impact factors and evolution paths in ESG disclosure and how to deal effectively with greenwashing.

Keywords Greenwashing · ESG disclosure · Evolutionary game · Tripartite players · Mechanism analysis

1 Introduction

> "ESG investing is facing a crisis of credibility due to rampant greenwashing. Until there are robust, enforceable standards, ESG will remain vulnerable to abuse by enterprises and intermediaries seeking to capitalize on investor demand without making meaningful changes."
> ——Mindy Lubber, CEO of Ceres (2024)

ESG disclosure is gaining prominence as it compels enterprises to disclose their ESG efforts for information symmetry (Aluchna et al., 2022). In the United States, the Securities and Exchange Commission (SEC) has proposed initiatives to mandate ESG disclosure for all publicly traded enterprises (Carattini et al., 2022). Meanwhile, the European Union's Sustainable Finance Disclosure Regulation (SFDR) focuses on standardizing ESG disclosure rules. To echo the initiative, France, the UK, Japan, and Sweden have also stepped up their efforts to promote ESG disclosure in their jurisdictions.

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However, the emergence of greenwashing challenges the original intention of ESG disclosure and the pace of sustainable business. Greenwashing refers to enterprises emphasizing their visible, positive environmental actions while neglecting or downplaying their less observable, potentially harmful activities (Wu et al., 2020). This discrepancy between the portrayed image and the actual implementation of ESG disclosure would entail misleading or overstated ESG claims, such as the ESG funds (Quinson, 2021), Bokswagen's Dieselgate scandal, BP's "Beyond Petroleum" campaign, H&M's "Conscious Collection", Danske Bank's ESG scandal (Carattini et al., 2022), which is eroding the credibility of ESG disclosure.

Although ESG greenwashing has been widely noticed irrespective of academic discourse or the business world, due to insufficient discussion in existing works, how to address this challenge remains uncertain for relevant practitioners, especially in light of the multiple stakeholders involved. To approach this gap, this study considers the strategic choices of each player and leverages evolutionary game theory (EGT) to unravel the decision-making mechanisms behind ESG greenwash behavior. The core research questions include:

1. Does a game equilibrium exist in the context of ESG disclosure and greenwashing? If so, what are the corresponding critical conditions? Understanding the concept of game equilibrium is crucial as it helps to identify stable states in the system, which can guide the design of effective regulatory mechanisms.
2. How do the strategies employed by investors and rating agencies, the 'tripartite players' in this context, affect enterprises' greenwashing in ESG disclosure? Moreover, how do the behavioral strategies of these players interact and shape the overall dynamics of the system?
3. Based on the impact factors such as regulatory policies, market forces, stakeholder expectations, and evolutionary paths of ESG disclosure, how can mechanisms be designed to guide and regulate the players' conduct effectively?

By innovatively applying the EGT to address these research questions, this study advances our understanding of the greenwashing phenomenon. It has important implications for governance practices aimed at curbing greenwashing across society. Furthermore, by examining the motivations and evolutionary paths of ESG disclosure through the lens of finite rationality, this study elucidates the formation mechanism from individual to collective behavior. It considers economic factors such as costs, interests, penalties, and more, vividly demonstrating how they constantly shape stakeholders' behavior and converge to equilibrium. Given the mutable and complex nature of ESG disclosure, it is pivotal to provide managers with precise information on how system trends are evolving, what potential conflicts can be mitigated, and how they contribute to the evolving landscape of ESG disclosure.

This study is structured as follows: Sect. 2 provides a literature review on EGT's application in sustainability, ESG disclosure, and greenwashing. Section 3 displays the detailed modeling process, including model description, payoff matrix, and replicator dynamic equations. Building upon the modeling work, Sect. 4 conducts an ESS analysis, followed by a stability analysis of tripartite players' strategies and an analysis of the influence mechanism of the parameters involved. Hereafter, a numerical simulation and in-depth discussions are shown in Sect. 5. Section 6 summarizes the critical findings, the marginal contributions, and the limitations.

2 Literature review

2.1 EGT and its application in sustainability research

EGT, initially developed by Maynard Smith and Price (Smith & Price, 1973), represents an extension of game theory that incorporates the study of dynamic conflicts (Tian & Sun, 2022). In real-world scenarios, participants often exhibit bounded rationality, which poses challenges to assuming complete rationality. Compared to traditional game theory, EGT considers this bounded rationality and focuses on dynamic equilibrium (Hao et al., 2022; Tan et al., 2023). This approach allows researchers to gain a deeper understanding of strategic interactions and their long-term outcomes, providing a practical framework for the simulation and analysis of complex economic phenomena, engineering, and management science systems (Xing et al., 2020; Zhao & Bai, 2021; Biancardi et al., 2021).

Sustainability challenges present inherent complexities involving multiple stakeholders with diverse objectives and constraints. In addressing these challenges, EGT enables social scientists with a powerful tool to accurately capture the nuances of decision-making processes for sustainability issues, encompassing various aspects such as decision analysis (Johari et al., 2019; Wang & Wang, 2022; Yu et al., 2023), business strategy (Ji et al., 2015; Kang et al., 2019), information system (Jacobides et al., 2021; Li et al., 2023a, 2023b, 2023c; Zhang et al., 2023), and management science (Coad, 2021; Gu et al., 2019; Kolokoltsov, 2017). In general, scholarly research has tended to analyze the game between 2 and 4 stakeholders within specific research boundaries, aiming to identify equilibrium strategies under contexts like low-carbon emission and transition, digital economy, and supply chain operations. However, it is essential to note that there remains a gap in the literature regarding leveraging EGT for ESG initiatives. While sustainability reporting and ESG performance are crucial for accountability and transparency, limited research addresses the game-theoretic dynamics of ESG disclosure. Additionally, developing specific regulations to govern greenwashing behavior needs to catch up, resulting in a grey area where organizations may engage in irresponsible practices without facing appropriate consequences. Given the prevalence and recurrence of greenwashing, there is an urgent need for specialized research on this phenomenon.

2.2 ESG disclosure

Since its inception in a United Nations report in 2006, ESG initiatives have garnered the attention of governments, businesses, and academics (Dai & Tang, 2022). Recognizing the importance of ESG factors, stakeholders and investors have shown a growing interest in accessing ESG reports to obtain critical information about an enterprise's sustainability performance. In response to this demand, many enterprises have voluntarily started providing ESG reports to enhance transparency and demonstrate their commitment to responsible business practices (Tsang et al., 2023). However, the availability and quality of the information need to be improved to effectively identify and assess ESG risks and opportunities (Ilhan et al., 2023; Khan, 2022). To address this issue, several countries have initiated mandatory ESG disclosure regulations to compel firms to provide high-quality information on ESG issues either alongside traditional financial disclosures or in separate specialized reports (Krueger et al., 2021). In addition to country-level initiatives, substantial efforts are being made at the global level to develop, standardize, and eventually enforce international ESG disclosure standards (Krueger et al., 2021), such as the Global Reporting Initiative (GRI),

Sustainability Accounting Standards Board (SASB), and International Integrated Reporting Council (IIRC).

ESG disclosure is a critical factor that influences vital performance indicators and has garnered significant attention from researchers seeking to understand its implications for enterprises. Previous studies have identified several positive outcomes associated with ESG disclosure. For instance, it has been supported that ESG disclosure reduces agency costs and enhances trust by reducing information asymmetry among investors and stakeholders (Dhaliwal et al., 2011; Simnett et al., 2009; Tsang et al., 2023). Moreover, some studies suggest that enterprises may utilize ESG disclosure to legitimize and compensate for poor performance (Busco et al., 2019) or manipulate their reputation (Ness & Mirza, 1991; Qiu et al., 2016), shedding light on potential strategic motivations behind ESG disclosure practices. This approach, in turn, creates value for enterprises by improving enterprise value (Alkaraan et al., 2022; Buallay, 2019; Dhaliwal et al., 2011; Girerd-Potin et al., 2014; Limkriangkrai et al., 2017; Naughton et al., 2019), mitigating risks (Chairani & Siregar, 2021; Kaiser & Welters, 2019; Li et al., 2022; Lueg et al., 2019), and enhancing earnings management (Rezaee & Tuo, 2019). However, it is noted that some studies, particularly in the developing economies, have indicated a negative association between ESG disclosure and enterprise value (Buallay, 2019; Buallay et al., 2020; Chen et al., 2018; Manchiraju & Rajgopal, 2017; Shane & Spicer, 1983). Additionally, using ESG disclosure as a form of reputation insurance may amplify negative market responses to announcements if those announcements erode stakeholders' trust (Bartov et al., 2021; Tsang et al., 2023). ESG disclosure can heighten enterprise litigation risks, particularly if stakeholders perceive the disclosed information as misleading or false (Tsang et al., 2023). Scholars have highlighted that institutional differences play a significant role in shaping the effectiveness of ESG disclosure (Avetisyan & Hockerts, 2017; Rytkönen & Louhiala-Salminen, 2014). Furthermore, factors such as profitability (Sharma et al., 2020), disclosure costs (Tsang et al., 2023), media coverage (Aerts et al., 2008; Hammami & Hendijani, 2020), and the presence of board committees (Arayssi et al., 2016; Cucari et al., 2018; Ismail & Latiff, 2019), also exert influence on ESG disclosure.

Although ESG disclosure is widely accepted and recognized as an essential measure of enterprise sustainability, its implications for enterprise performance remain controversial. To gain a deeper understanding of the dynamics, it is crucial to develop a comprehensive framework that considers multiple factors, which should encompass not only the impact on interests but also the broader contextual factors that shape strategic decision-making regarding ESG disclosure, such as regulatory requirements, the rating agencies' standards, and stakeholders' preferences.

2.3 Greenwashing

Greenwashing has evolved in response to growing pressures from stakeholders and investors for enterprises to enhance their environmental credentials and reporting practices. Research has diligently kept pace with these shifts. Previous research has primarily approached greenwashing as a phenomenon targeting consumers, with a focus on defining what greenwashing entails (de Freutas Netto et al., 2020) and examining its profitability for businesses (Li et al., 2023a, 2023b, 2023c) while highlighting its detrimental effects on society (Haack et al., 2021; Piccolo et al., 2015). However, greenwashing is not always negative. In some cases, it can yield short-term profitability, which elucidates why enterprises resort to such practices (Montgomery et al., 2023).

As more stakeholders become involved in greenwashing, research has highlighted the diverse and intricate interactions between enterprises and their stakeholders. Table 1 summarizes related greenwashing research. One crucial aspect explored by researchers in these studies is the interdependent relationship between enterprises and governments (Sun & Zhang, 2019). Governments hold significant influence over access to resources and the regulations governing environmental and social activities, putting them in the spotlight (Montgomery et al., 2023). However, enterprises may also present their legally mandated transparency enhancements as evidence of their virtuous practices (Leung & Snell, 2021) to respond to regulatory pressures using greenwashing tactics (Setia et al., 2015).

The prevalence of greenwashing also presents a substantial obstacle to the progress of ESG goals (Montgomery et al., 2023). Greenwashing can potentially distort ESG investments (Glaeser & Ujhelyi, 2010), leading to a mismatch between expected and actual returns. However, this issue has been underexplored from an investor's perspective. This situation highlights the urgent need for investors to move beyond superficial ESG claims and find ways to identify genuine ESG efforts. Meanwhile, divergences in evaluation criteria and methodologies among rating agencies, such as MSCI, Sustainalytics, and Down Jones Sustainability Indices (DJSI), create an environment where enterprises can engage in opportunistic greenwashing practices. This compromises the comparability, credibility, and usefulness of ESG disclosure (Tsang et al., 2023), which may hinder investors' decision-making processes (Berg et al., 2022). Indeed, rating agencies grapple with the dilemma of strictly disclosing ESG information based on comprehensive inputs or colluding with enterprises to reduce costs and effort (He et al., 2020; Liu et al., 2023). The complex interactions and decision-making processes among investors and rating agencies further amplify the uncertainties of enterprises' strategies in ESG disclosure, which is still an open question but is the focus of this study.

Table 1 Related research on greenwashing

Reference	Focus	Key stakeholders
Sun and Zhang (2019)	Government regulations	Heterogeneous enterprises with the strategy of green innovation and greenwashing, respectively
Wu et al. (2020)	Corporate social responsibility and information transparency	Enterprises and consumers
Huang et al. (2020)	Government regulations	Enterprises, consumers, and governments in emerging markets
Pizzetti et al. (2021)	Greenwashing locus	Enterprises and suppliers
Liu et al. (2023)	Governance mechanism	Governments, certification authorities, and manufacturers of electric vehicles
He et al. (2020)	Government regulations	Contractors, project supervisors, and external regulators
Li et al. (2024)	The role of blockchain in curbing greenwashing	Enterprises, green financial institutions, and governments
Liu et al. (2024)	Government regulations	Governments, enterprises, and investors
Lee and Raschke (2023)	Stakeholder legitimacy in greenwashing and financial performance	Enterprises and stakeholders

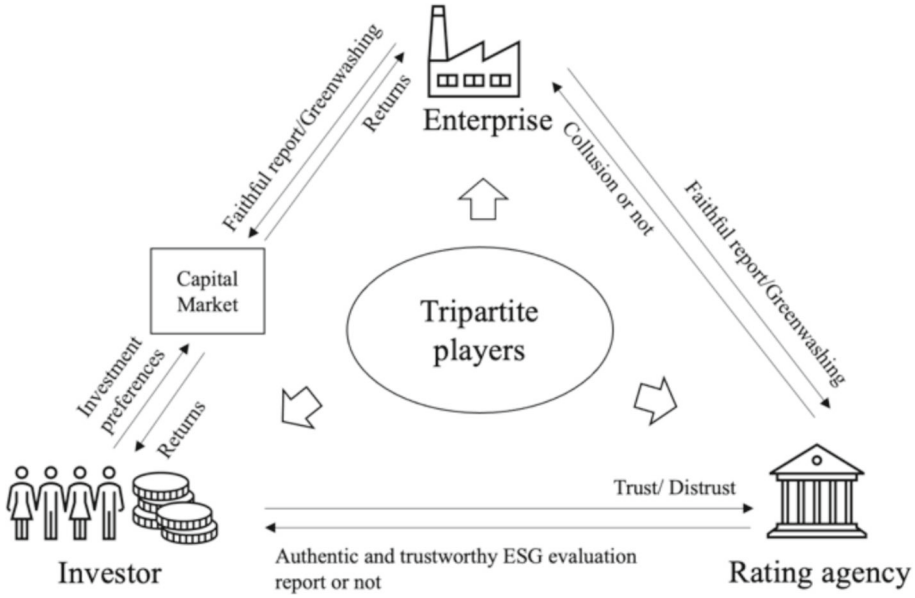

Fig. 1 Theoretical modeling framework

3 Modeling

3.1 Model formulation

3.1.1 Strategies

In the context of ESG disclosure, the enterprise exhibits varying behaviors. Some enterprises report their ESG efforts faithfully, while others use greenwashing by overstating their actual ESG efforts. Thus, we consider a strategy set for the enterprise consisting of two options (Faithful reporting (FR) and Greenwashing (GW)). Investors have different preferences for the adoption of ESG reports. Here, we assume the strategy set includes (Trust, Distrust). Specifically, the strategy "Trust" implies that the investor will rely on the ESG reports when it makes investment decisions. Otherwise, the investor would depend on his judgment. The strategy set of the rating agency consists of (Strict evaluation (SE), Non-strict evaluation (NE)). In the case of "SE", the rating agency undertakes thorough data collection and comprehensive evaluation indicators to assess the ESG efforts of the enterprise, ensuring the validity and authenticity of the published reports. However, opting for "NE" signifies that the rating agency may exert limited efforts in the evaluation process, potentially leading to biased results. Figure 1 illustrates the strategy set framework in this tripartite model.

3.1.2 Costs

The enterprise incurs various costs, encompassing both time and human resources, related to ESG accounting and disclosure to the public, and in this study, we denote the fixed expense as C_0. Besides, when the enterprise opts for greenwashing behavior, there is a risk of regulatory penalties. The evaluation results provided by the ESG rating agency play a crucial role

in detecting greenwashing, such as discrepancies between enterprise disclosure and ESG evaluation reports. Thus, we assume that when the rating agency chooses "SE", the potential loss, including administrative penalty and reputational loss, is represented by $\alpha_1 P_1$. Similarly, the loss is recorded as $\alpha_2 P_1$ when the rating agency chooses "NE". Here, α_1 and α_2 are intensity coefficients indicating the extent to which the rating agency discloses enterprise ESG efforts, $\alpha_1 > \alpha_2$ and $\alpha_1, \alpha_2 \in (0,1)$.

As for the investor, the decision options of "Trust" and "Distrust" entail different investment costs, namely C_1 and C_2. If the ESG rating agency opts for "NE", we assume the incurred cost to be C_3. Like the enterprise, the rating agency encounters potential penalties from the regulator and the loss from the enterprise and investor, which is denoted by βP_2, where β is the regulatory intensity for the ESG rating agency. When the ESG rating agency prefers "SE", an additional cost occurs due to increased expenses related to data verification, ESG accounting, etc. We represent this additional cost as ΔC. Hence, the total cost incurred by the ESG rating agency choosing "SE" is $C_3 + \Delta C$.

3.1.3 Returns

The expected returns of the enterprise comprise returns from administrative sectors and investment returns from the investor. Specifically, focusing on the returns provided by administrative sectors, we denote it as I_1 when the enterprise chooses "FR". However, when the strategy switches to "GW", the expected return becomes $I_1 + \Delta I_1$ due to the overstatement of ESG efforts if rating agencies chooses "NE". The return from the investor side varies based on the investor's strategic preferences. If the investor opts for "Distrust," the expected returns for the enterprise from the investor side are denoted as I_2, regardless of the strategy choices made by the ESG rating agency. When the investor prefers "Trust" with "SE" chosen by the rating agency, the enterprise's return from the investor is denoted as $I_3 (I_3 > I_2)$. However, if the rating agency chooses "NE", the irresponsible behavior exacerbates the negative effect of greenwashing, leading to a "self-deception" dilemma. In this scenario, the enterprise returns more benefits from the investor, and the return is represented as $I_3 + \Delta I_3$.

The return of the investor stems from the investment return on the enterprise. When the investor chooses "Distrust", indicating that it makes investment decisions based on personal judgment, the return from investors' professionalism is recorded as I_4. On the other hand, if the investor prefers "Trust" in the rating agency, and the enterprise decides to disclose its ESG efforts faithfully, the return of relying on rating agencies is represented by I_5, regardless of the rating agency's strategy choices. However, if the enterprise chooses "GW" with "NE" chosen by the rating agency, due to information asymmetry and limited real ESG efforts by the enterprise, the investment returns of the investor on the enterprise decrease. In this case, we denote the expected return as I_5', where $I_5 > I_5' > 0$. Conversely, if the rating agency chooses "SE", it facilitates information symmetry, and the investor's return is denoted as I_5.

As for the rating agency, its returns come from the attention of the enterprise and the investor. When the rating agency opts for "SE", the returns from market transactions (offering consultatory service, selling reports, etc.) with the enterprise under "FR" and "GW" are respectively recorded as I_6 and I_6'. Likewise, the reputational benefits from investors with "Trust" and "Distrust" are denoted as I_7 and 0, severally. If the rating agency chooses "NE", the market transaction return from the enterprise's "FR" is I_8, while I_8' represents the return when the enterprise chooses the opposite strategy. Besides, we adopt I_9 to denote the reputational return from the investor with "Trust", and we assume the return from the investor is 0 when the investor chooses "Distrust." Here, we assume $I_6 > I_8$, $I_7 > I_9$, and $I_6' > I_8'$.

3.1.4 Strategic assumptions

The model in this study considers tripartite players with bounded rationality, allowing them to adjust their strategy choices based on expected returns. We assume the share of the enterprise choosing "FR" is represented by x. Accordingly, the share of choosing "GW" is $1 - x$. Similarly, y represents the investor's proportion of choosing "Trust", while the share of choosing the alternative decision direction is $1 - y$. Besides, the proportion of the ESG rating agency choosing "SE" and "NE" are denoted as z and $1 - z$, respectively. Here, x, y, $z \in [0,1]$.

The descriptions of the symbols used in this model are displayed in Table 2.

Table 2 Symbols summary

Symbols	Definitions
The enterprise	
x	Proportion of enterprises' choosing "FR" strategy
C_0	Fixed costs
P_1	Loss of "GW" strategy(including penalty and reputational loss)
I_1, ΔI_1	Returns from administrative sector of "FR" and "GW" strategies, respectively
I_2	Returns if the investor opts for "Distrust" strategy
I_3, ΔI_3	Returns of "FR" strategy if the investor prefers "Trust" strategy under the rating agency's "SE" strategy, and extra returns of "GW" strategy if the investor prefers "Trust" strategy under the rating agency's "NE" strategy, respectively
The investor	
y	Proportion of investors' choosing "Trust" strategy
C_1, C_2	Investment costs of "Trust" and "Distrust" strategies, respectively
I_4, I_5,I_5'	Investment returns from professional judgement of "Distrust" strategy, investment returns of relying on rating agencies of "Trust" strategy, and investment returns if the enterprise chooses "GW" strategy under the rating agency's "NE" strategy, respectively
The rating agency	
z	Proportion of rating agency's choosing "SE" strategy
C_3	Costs of "NE" strategy
P_2	Loss of "NE" strategy(including penalty and trust loss)
α_1, α_2	Disclosure intensity of "SE" and "NE" strategies, respectively
ΔC	Extra costs of "SE" strategy
β	External supervision intensity for the rating agency
I_6, I_6'	Market returns of "SE" strategy if the enterprise opts for "FR" and "GW" strategies, respectively
I_8, I_8'	Market returns of "NE" strategy if the enterprise opts for "FR" and "GW" strategies
I_7, I_9	Reputation returns of "SE" strategy and "NE" strategy if the investor opts for "Trust" strategy, respectively

Table 3 The portfolio strategies and payoff matrix

Strategy combination	Payoff of enterprise	Payoff of investor	Payoff of rating agency
(FR, Trust, SE)	$I_1 + I_3 - C_0$	$I_5 - C_1$	$I_6 + I_7 - C_3 - \Delta C$
(FR, Trust, NE)	$I_1 + I_3 - C_0$	$I_5 - C_1$	$I_8 + I_9 - C_3 - \beta P_2$
(FR, Distrust, SE)	$I_1 + I_2 - C_0$	$I_4 - C_2$	$I_6 - C_3 - \Delta C$
(FR, Distrust, NE)	$I_1 + I_2 - C_0$	$I_4 - C_2$	$I_8 - C_3 - \beta P_2$
(GW, Trust, SE)	$I_1 + I_3 - C_0 - \alpha_1 P_1$	$I_5 - C_1$	$I_6' + I_7 - C_3 - \Delta C$
(GW, Trust, NE)	$I_1 + \Delta I_1 + I_3 + \Delta I_3 - C_0 - \alpha_2 P_1$	$I_5' - C_1$	$I_8' + I_9 - C_3 - \beta P_2$
(GW, Distrust, SE)	$I_1 + I_2 - C_0 - \alpha_1 P_1$	$I_4 - C_2$	$I_6' - C_3 - \Delta C$
(GW, Distrust, NE)	$I_1 + \Delta I_1 + I_2 - C_0 - \alpha_2 P_1$	$I_4 - C_2$	$I_8' - C_3 - \beta P_2$

3.2 Payoff matrix

Based on the model description, Table 3 presents the portfolio strategies and related potential payoff matrices by the investor and rating agency, taking into account the strategic choices of the enterprise ("FR" or "GW").

3.3 Replicator dynamics system

In EGT, the replicator dynamic system is a fundamental concept that helps describe the dynamics of strategy frequencies within a population (Friedman, 1991). It has proven to be a valuable tool for studying the dynamics of strategic interactions and the evolution of behaviors across various contexts (Chen & Hu, 2018; Xiao & Yu, 2006). This study gives us a prominent framework for investigating the evolution of players' behaviors in ESG disclosure.

Here, Y_{E1} and Y_{E2} represent the expected profits of the enterprise with strategies "FR" and "GW", respectively. Also, the average expected profit of the enterprise is denoted as $\overline{Y}_E$. Therefore,

$$Y_{E1} = I_1 - C_0 + yI_3 + (1-y)I_2 \tag{1}$$

$$Y_{E2} = I_1 + (1-z)\Delta I_1 + yI_3 + (1-y)I_2 + y(1-z)\Delta I_3 - C_0 - z\alpha_1 P_1 - (1-z)\alpha_2 P_1 \tag{2}$$

$$\overline{Y}_E = x \cdot Y_{E1} + (1-x)Y_{E2} \tag{3}$$

Likewise, we adopt Y_{I1} and Y_{I2} to denote the investor's expected profits of choosing "Trust" and "Distrust", respectively. $\overline{Y}_I$ is the average expected profit. Hence,

$$Y_{I1} = x(I_5 - C_1) + (1-x)\left[zI_5 + (1-z)I_5'\right] - (1-x)C_1 \tag{4}$$

$$Y_{I2} = I_4 - C_2 \tag{5}$$

$$\overline{Y}_I = y \cdot Y_{I1} + (1-y)Y_{I2} \tag{6}$$

Regarding the rating agency, Y_{R1} and Y_{R2} represent its expected profits with strategies "SE" and "NE", severally. Also, the average expected profit is denoted as $\overline{Y}_R$. Therefore,

$$Y_{R1} = yI_7 + x(I_6 - C_3 - \Delta C) + (1-x)(I_6' - C_3 - \Delta C) \tag{7}$$

$$Y_{R2} = yI_9 + xI_8 + (1-x)I_8' - (C_3 + \beta P_2) \tag{8}$$

$$\overline{Y}_R = z \cdot Y_{R1} + (1-z)Y_{R2} \tag{9}$$

Based on the Eqs. (1)-(9), the replicator dynamics system of this evolutionary game model is presented as follows:

$$\begin{aligned} F(x) = \frac{dx}{dt} &= x\left(Y_{E1} - \overline{Y}_E\right) \\ &= x(1-x)\left[z\alpha_1 P_1 + (1-z)\alpha_2 P_1 - (1-z)\Delta I_1 - y(1-z)\Delta I_3\right] \end{aligned} \tag{10}$$

$$F(y) = \frac{dy}{dt} = y\left(Y_{I1} - \overline{Y}_I\right) = y(1-y)\{xI_5 + (1-x)\left[zI_5 + (1-z)I_5'\right] - I_4 + C_2 - C_1\} \tag{11}$$

$$\begin{aligned} F(z) = \frac{dz}{dt} &= z\left(Y_{R1} - \overline{Y}_R\right) \\ &= z(1-z)\left[y(I_7 - I_9) + x(I_6 - I_8) + (1-x)(I_6' - I_8') + \beta P_2 - \Delta C\right] \end{aligned} \tag{12}$$

4 Model analysis

4.1 ESS analysis

A stable solution represents a strategy that is resistant to invasion by alternative strategies. According to the Jacobian Matrix, ESS corresponds to a strict Nash equilibrium point, commonly referred to as a "sink" point, while the others are considered "source" points (Selten, 1988; Tian & Sun, 2022). The Jacobian matrix could capture the local behavior of the replicator dynamics system by providing information about the rates of change of strategy frequencies and their effects on each other. Thus, we employ the Jacobian matrix to investigate the ESS of tripartite players within the ESG disclosure system. According to the replicator dynamics system, the Jacobian matrix of our model is

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

where,

$$J_{11} = (1-2x)[z\alpha_1 P_1 + (1-z)\alpha_2 P_1 - (1-z)\Delta I_1 - y(1-z)\Delta I_3]$$

$$J_{12} = -x(1-x)(1-z)\Delta I_3$$

$$J_{13} = x(1-x)[\Delta I_1 + y\Delta I_3 + \alpha_1 P_1 - \alpha_2 P_1]$$

$$J_{21} = y(1-y)\{I_5 - [zI_5 + (1-z)I_5']\}$$

$$J_{22} = (1-2y)\{xI_5 + (1-x)\left[zI_5 + (1-z)I_5'\right] - I_4 + C_2 - C_1\}$$

$$J_{23} = y(1-y)(1-x)(I_5 - I_5')$$

$$J_{31} = z(1-z)[(I_6 - I_8) - (I_6' - I_8')]$$

$$J_{32} = z(1-z)(I_7 - I_9)$$

$$J_{33} = (1-2z)[y(I_7 - I_9) + x(I_6 - I_8) + (1-x)(I_6' - I_8') + \beta P_2 - \Delta C]$$

In addition, eight pure strategy equilibrium points are synthesized in the EGT model of this study following the judgment criteria proposed by Lyapunov (1992) and Ritzberger and Weibull (1995). These points, which satisfy all eigenvalues of the Jacobian matrix being non-positive, are likely to be ESSs. Combined with basic assumptions proposed in model description—$\alpha_1 > \alpha_2$, $I_3 > I_2$, $I_5 > I_5'$, $I_6 > I_8$, $I_7 > I_9$, $I_6' > I_8'$, a detailed analysis is presented in Table 4. Furthermore, after elaborating on eight distinct scenarios, Table 5 identifies the ESSs and their corresponding critical conditions.

Based on Tables 4, 5, it is observed that six of eight equilibrium points could become ESS include E_1(0,0, 0), E_3(0,1, 0), E_5(1,0, 0), E_6(1,0, 1), E_7(1,1, 0), E_8(1,1, 1). These ESSs demonstrate that the ESG disclosure system still lacks a unified and effective regulatory instrument, which consequently leads to the diversity of strategy choices of involved agents. To be specific, when $\alpha_2 P_1 - \Delta I_1 < 0$, $I_5' - I_4 + C_2 - C_1 < 0$, $I_6' - I_8' + \beta P_2 - \Delta C < 0$, that is, the administrative penalty for enterprise's GW is less than the expected gains with rating agencies' NE, the net profit under the investor's trust is lower than that under the distrust strategy when the enterprise' GW colludes with rating agencies' NE, and rating agencies' net profits with SE is lower than that with NE when GW and distrust are chosen by enterprises and investor, respectively. (0,0,0) will be one of the ESSs at this point. Here, a typical dilemma in ESG dilemma will arise—enterprises masquerading as green businesses, rating agencies failing to strictly audit, and loss of investor trust.

Meanwhile, the potential to resolve this dilemma is recognized. When $I_5 - I_4 + C_2 - C_1 > 0$, $I_7 - I_9 + I_6 - I_8 + \beta P_2 - \Delta C > 0$, it indicates that the net profit of investor' trust is greater than that of distrust strategy under enterprise's honest reporting. In this scenario, rating agencies' SE will receive more returns than choosing NE with enterprises' FR and investor's trust strategy. Consequently, it is foreseeable that the ESG disclosure system will head toward the ideal state (1,1,1) characterized by honest disclosure of enterprises, strict evaluation by rating agencies and devoted investors. However, approaching the ideal state still needs more efforts to steer the involved stakeholders' behavior, such as actor-based policymaking, mechanism design, etc. Therefore, in Sects. 4.2 and 5, we conduct the interplay analysis and influence factor analysis regarding the players' behavioral decisions, laying the groundwork for a tailored policy design and agents' behavior cultivation.

4.2 Interactions analysis

In this subsection, we seek to elucidate the strategy interaction mechanism based on the dynamic strategy choice process of each subject, such as how the strategy choice of enterprises is affected by the investors' and rating agencies' strategies, thus identifying the key regulatory subject as the trigger. To arrive at this research objective, the analyses from the perspectives of involved firms, investors, and rating agencies within the ESG disclosure system are conducted in Sects. 4.2.1, 4.2.2, and 4.2.3, respectively.

Table 4 Stability analysis of each equilibrium point

Equilibrium points	Eigenvalues	Local stability results
$E_1(0,0,0)$	$\lambda_1 : \alpha_2 P_1 - \Delta I_1$ $\lambda_2 : I_5' - I_4 + C_2 - C_1$ $\lambda_3 : (I_6' - I_8') + \beta P_2 - \Delta C$	Conditional ESS
$E_2(0,0,1)$	$\lambda_1 : \alpha_1 P_1$ $\lambda_2 : I_5 - I_4 + C_2 - C_1$ $\lambda_3 : -[(I_6' - I_8') + \beta P_2 - \Delta C]$	Unstable point
$E_3(0,1,0)$	$\lambda_1 : \alpha_2 P_1 - \Delta I_1 - \Delta I_3$ $\lambda_2 : -[I_5' - I_4 + C_2 - C_1]$ $\lambda_3 : (I_7 - I_9) + (I_6' - I_8') + \beta P_2 - \Delta C$	Conditional ESS
$E_4(0,1,1)$	$\lambda_1 : \alpha_1 P_1 v$ $\lambda_2 : -[I_5 - I_4 + C_2 - C_1]$ $\lambda_3 : -[(I_7 - I_9) + (I_6' - I_8') + \beta P_2 - \Delta C]$	Unstable point
$E_5(1,0,0)$	$\lambda_1 : -(\alpha_2 P_1 - \Delta I_1)$ $\lambda_2 : I_5 - I_4 + C_2 - C_1$ $\lambda_3 : I_6 - I_8 + \beta P_2 - \Delta C$	Conditional ESS
$E_6(1,0,1)$	$\lambda_1 : -\alpha_1 P_1$ $\lambda_2 : I_5 - I_4 + C_2 - C_1$ $\lambda_3 : -[I_6 - I_8 + \beta P_2 - \Delta C]$	Conditional ESS
$E_7(1,1,0)$	$\lambda_1 : -(\alpha_2 P_1 - \Delta I_1 - \Delta I_3)$ $\lambda_2 : -(I_5 - I_4 + C_2 - C_1)$ $\lambda_3 : I_7 - I_9 + I_6 - I_8 + \beta P_2 - \Delta C$	Conditional ESS
$E_8(1,1,1)$	$\lambda_1 : -\alpha_1 P_1$ $\lambda_2 : -(I_5 - I_4 + C_2 - C_1)$ $\lambda_3 : -[(I_7 - I_9) + I_6 - I_8 + \beta P_2 - \Delta C]$	Conditional ESS

4.2.1 The strategy choices of the enterprise

Based on the stability theorem of differential equations, the conditions for the enterprise's evolutionary equilibrium strategy include $F(x) = 0$, $F'(x) < 0$. Here, $F(x) = x(1-x)[z\alpha_1 P_1 + (1-z)\alpha_2 P_1 - (1-z)\Delta I_1 - y(1-z)\Delta I_3]$, $F'(x) = (1-2x)[z\alpha_1 P_1 + (1-z)\alpha_2 P_1 - (1-z)\Delta I_1 - y(1-z)\Delta I_3]$. Therefore,

Proposition 1.1 When $y > y_0$, the equilibrium strategy of the enterprise is "GW". While, if $y < y_0$, the equilibrium strategy by the enterprise is "FR". Therein, $y_0 = \frac{z\alpha_1 P_1 + (1-z)\alpha_2 P_1 - (1-z)\Delta I_1}{(1-z)\Delta I_3}$.

Proof 1.1 We assume $H(y) = -y(1-z)\Delta I_3 + z\alpha_1 P_1 + (1-z)\alpha_2 P_1 - (1-z)\Delta I_1$, Due to y, $z \in [0,1]$, $\Delta I_3 > 0$, $H(y)$ is a monotonically decreasing function of y. Consequently, when $y > y_0$, $H(y) < H(y_0)$. In this case, $F(x)|_{x=0} = 0$, and $F'(x)|_{x=0} < 0$. $x = 0$ is thus the equilibrium strategy for the enterprise. Similarly, when $y < y_0$, $H(y) > H(y_0)$. As a

Table 5 ESS and corresponding conditions

Scenarios	Conditions	Potential ESS
Scenario 1	$\alpha_2 P_1 - \Delta I_1 < 0$	$E_1(0,0,0)$
	$I_5' - I_4 + C_2 - C_1 < 0$	$E_6(1,0,1)$, $E_8(1,1,1)$
	$(I_6' - I_8') + \beta P_2 - \Delta C < 0$	
Scenario 2	$\alpha_2 P_1 - \Delta I_1 - \Delta I_3 < 0$	$E_3(0,1,0)$, $E_8(1,1,1)$
	$-(I_5' - I_4 + C_2 - C_1) < 0$	
	$(I_7 - I_9) + (I_6' - I_8') + \beta P_2 - \Delta C < 0$	
Scenario 3	$-(\alpha_2 P_1 - \Delta I_1) < 0$	$E_5(1,0,0)$
	$I_5 - I_4 + C_2 - C_1 < 0$	
	$I_6 - I_8 + \beta P_2 - \Delta C < 0$	
Scenario 4	$I_5 - I_4 + C_2 - C_1 < 0$	$E_1(0,0,0)$, $E_6(1,0,1)$
	$-[I_6 - I_8 + \beta P_2 - \Delta C] < 0$	
Scenario 5	$-(\alpha_2 P_1 - \Delta I_1 - \Delta I_3) < 0$	$E_7(1,1,0)$
	$-(I_5 - I_4 + C_2 - C_1) < 0$	
	$I_7 - I_9 + I_6 - I_8 + \beta P_2 - \Delta C < 0$	
Scenario 6	$-(I_5 - I_4 + C_2 - C_1) < 0$	$E_1(0,0,0)$
	$-[(I_7 - I_9) + I_6 - I_8 + \beta P_2 - \Delta C] < 0$	$E_3(0,1,0)$, $E_8(1,1,1)$

result, $x = 1$ is the equilibrium state for the enterprise's strategy choice due to $F(x)|_{x=0} = 0$ and $F'(x)|_{x=0} < 0$. Regarding the case of $y = y_0$, the equilibrium state is uncertain for the enterprise as all potential choices would be stable.

Proposition 1.2 When $z > z_0$, the equilibrium strategy of the enterprise is "FR". When $z < z_0$, "GW" is the equilibrium strategy for the enterprise. Therein, $z_0 = \frac{\Delta I_1 + y\Delta I_3 - \alpha_2 P_1}{y\Delta I_3 + (\alpha_1 - \alpha_2)P_1 + \Delta I_1}$.

Proof 1.2 We assume $H(z) = z\alpha_1 P_1 + (1-z)\alpha_2 P_1 - (1-z)\Delta I_1 - y(1-z)\Delta I_3$, by simplifying that is $H(z) = [y\Delta I_3 + (\alpha_1 - \alpha_2)P_1 + \Delta I_1]z - \Delta I_1 - y\Delta I_3 + \alpha_2 P_1$. Based on the basic assumptions, $\alpha_1 > \alpha_2$, y, ΔI_3, ΔI_1, $P_1 > 0$. $H(z)$ is, therefore, a monotonically increasing function for z. Furthermore, if $z > z_0$, it is found that $H(z) > H(z_0)$. In this case, $F(x)|_{x=1} = 0$, and $F'(x)|_{x=1} < 0$. Furthermore, $x = 1$ is the equilibrium strategy for the enterprise. Also, when $z < z_0$, $H(z) < H(z_0)$, $F(x)|_{x=0} = 0$, and $F'(x)|_{x=0} < 0$. And $x = 0$ is the equilibrium strategy. When $z = z_0$, we cannot assure the equilibrium strategy of the enterprise because all the choices would be stable.

Based on Proposition 1.1 and Proposition 1.2, strict evaluations by ESG rating agencies can effectively deter enterprises from engaging in greenwashing. This indicates that strengthening oversight and supervision of these agencies could be a viable measure against greenwashing. It can "kill two birds with one stone": (i) promoting the integrity and credibility of enterprises' self-reported ESG disclosures, making it harder to misrepresent performance; and (ii) encouraging rating agencies to uphold high evaluation standards through improved accountability. In contrast, investors' trust may breed the greenwashing behavior of enterprises due to incremental gains. Therefore, regulatory strategies targeting rating agencies are preferable for curbing enterprise misconduct.

4.2.2 The strategy choices of the investor

Likewise, regarding the strategy stability of the investor, the critical conditions for arriving at the equilibrium strategy are $F(y) = 0$, $F'(y) < 0$. To be specific, $F(y) = y(1-y)\{xI_5 + (1-x)\left[zI_5 + (1-z)I_5'\right] - I_4 + C_2 - C_1\}$, $F'(y) = (1-2y)\{xI_5 + (1-x)\left[zI_5 + (1-z)I_5'\right] - I_4 + C_2 - C_1\}$. Hence,

Proposition 2.1 Regarding the investor, when, the equilibrium strategy is "Trust", while, the equilibrium strategy is "Distrust". Therein, the threshold.

$x > x_0 x < x_0 x_0 = \frac{zI_5+(1-z)I_5'-I_4+C_2-C_1}{zI_5+(1-z)I_5'-I_5}$

Proof 2.1 Here, we assume $\varphi(x) = xI_5 + (1-x)\left[zI_5 + (1-z)I_5'\right] - I_4 + C_2 - C_1$, simplifying as $\varphi(x) = (1-z)(I_5 - I_5')x + zI_5 + (1-z)I_5' - I_4 + C_2 - C_1$. Due to $I_5 > I_5'$ and $z \in [0,1]$, $\varphi(x)$ is a monotonically increasing function for x. Then, when $x > x_0$, $\varphi(x) > \varphi(x_0)$. Therefore, $F(y)|_{y=1} = 0$, and $F'(y)|_{y=1} < 0$. It is found that $y = 1$ is the equilibrium strategy for the investor. And if $x < x_0, \varphi(x) < \varphi(x_0)$, it is detected that $y = 0$ is the equilibrium strategy of the investor due to $F(y)|_{y=0} = 0$, and $F'(y)|_{y=0} < 0$. However, when $x = x_0$, the equilibrium strategy is uncertain as all choices would be stable.

Proposition 2.2 When $z > z_0$, the equilibrium strategy of the investor is "Trust". When $z < z_0$, the equilibrium strategy of the investor is "Distrust". Therein,$z_0 = \frac{xI_5+(1-x)I_5'-I_4+C_2-C_1}{(1-x)(I_5'-I_5)}$.

Proof 2.2 We assume $\varphi(z) = xI_5 + (1-x)\left[zI_5 + (1-z)I_5'\right] - I_4 + C_2 - C_1$, to simplify, $\varphi(z) = (1-x)\left(I_5 - I_5'\right)z + xI_5 + (1-x)I_5' - I_4 + C_2 - C_1$. Considering that $I_5 > I_5'$ and $x \in [0,1]$, $\varphi(z)$ is a monotonically increasing function concerning z. When $z > z_0$, $\varphi(z) > \varphi(z_0)$, $F(y)|_{y=1} = 0$, and $F'(y)|_{y=1} < 0$. Consequently, $y = 1$ is the equilibrium strategy for the investor. On the other hand, when $z < z_0$, $\varphi(z) < \varphi(z_0)$, $F(y)|_{y=0} = 0$, and $F'(y)|_{y=0} < 0$. At this time, $y = 0$ is the equilibrium strategy for the investor.

Building on Propositions 2.1 and 2.2, it is evident that both faithful disclosure by enterprises and strict assessment by rating agencies are critical for strengthening investors' confidence in ESG reporting. Conversely, the observed greenwashing behavior of enterprises and the biased evaluation by rating agencies will undermine investors' trust in the integrity of the ESG information landscape. Therefore, safeguarding the independence and impartiality of ESG rating agencies should be a paramount priority. This is vital to ensure they effectively serve as credible and trustworthy intermediaries of enterprises' ESG performance.

4.2.3 The strategy choices of the ESG rating agency

About the ESG rating agency, the conditions for the ESG rating agency's equilibrium strategy are $F(z) = 0, F'(z) < 0$. Here, $F(z) = z(1-z)[y(I_7 - I_9) + x(I_6 - I_8) + (1-x)(I_6' - I_8') + \beta P_2 - \Delta C]$, and $F'(z) = (1-2z)[y(I_7 - I_9) + x(I_6 - I_8) + (1-x)(I_6' - I_8') + \beta P_2 - \Delta C]$. Therefore,

Proposition 3.1 When $I_6 - I_8 > I_6' - I_8'$, if $x > x_0$, the ESG rating agency's equilibrium strategy is "SE", if $x < x_0$, the equilibrium strategy will switch to "NE". And when $I_6 - I_8 < I_6' - I_8'$, if $x > x_0$, the equilibrium strategy of the ESG rating agency is "NE", if $x < x_0$, the equilibrium strategy of the ESG rating agency is "SE". Here, $x_0 = \frac{(I_6'-I_8')+y(I_7-I_9)+\beta P_2-\Delta C}{(I_6'-I_8')-(I_6-I_8)}$.

Proof 3.1 We assume $Q(x) = \left[(I_6 - I_8) - \left(I_6' - I_8'\right)\right]x + \left(I_6' - I_8'\right) + y(I_7 - I_9) + \beta P_2 - \Delta C$, if $I_6 - I_8 > I_6' - I_8'$, $Q(x)$ is a monotonically increasing function concerning x. When $x > x_0$, $Q(x) > Q(x_0)$, it is observed that $F(z)|_{z=1} = 0$, and $F'(z)|_{z=1} < 0$. Hence, $z = 1$ is the equilibrium strategy for the ESG rating agency. When $x < x_0$, $Q(x) < Q(x_0)$, it is noticed that $F(z)|_{z=0} = 0$, and $F'(z)|_{z=0} < 0$. In this case, $z = 0$ is the equilibrium strategy for the ESG rating agency. If $I_6 - I_8 < I_6' - I_8'$, $Q(x)$ is a monotonically decreasing function for x. This proposition could be demonstrated in similar steps.

Proposition 3.2 When $y > y_0$, the ESG rating agency's equilibrium strategy is "SE", when $y < y_0$, the equilibrium strategy of the ESG rating agency is "NE". The threshold $y_0 = -\frac{x(I_6 - I_8) + (1-x)(I_6' - I_8') + \beta P_2 - \Delta C}{I_7 - I_9}$.

Proof 3.2 We assume $Q(y) = y(I_7 - I_9) + x(I_6 - I_8) + (1 - x)(I_6' - I_8') + \beta P_2 - \Delta C$. As the assumptions mentioned previously, $I_7 > I_9$, thus, $Q(y)$ is a monotonically increasing function for y. When $y > y_0$, $Q(y) > Q(y_0)$, $F(z)|_{z=1} = 0$, and $F'(z)|_{z=1} < 0$. Therefore, $z = 1$ is the equilibrium strategy for the ESG rating agency. When $y < y_0$, $Q(y) < Q(y_0)$, it is detected that $F(z)|_{z=0} = 0$, and $F'(z)|_{z=0} < 0$. Here, $z = 0$ is the equilibrium strategy for the ESG rating agency.

Propositions 3.1 and 3.2 elucidate the interdependent dynamics between investor trust and the strategic choices of ESG rating agencies. These propositions suggest that investor trust facilitates and encourages ESG raters to undertake rigorous scrutiny of enterprises' ESG disclosures. Simultaneously, it is acknowledged that enterprises can also influence the strategy choices of ESG raters. However, the nature and extent of this influence may vary across scenarios, contingent on factors such as the regulatory environment and market dynamics.

In a nutshell, as illustrated in Fig. 2, the interplay between various actors in the ESG greenwashing system is complex. The rigorous scrutiny conducted by rating agencies represents the first critical element in moving toward the ideal state of "no greenwashing". This rigorous scrutiny is associated with a positive feedback loop between investor trust and rating agency diligence. Although the reverse influence is determined by specific parameters, the "SE" by rating agencies stimulates enterprises to choose "FR", which in turn encourages investors to choose "Trust". However, investors' trust cannot yield enterprises' honesty, instead, greenwashing behavior might be taken due to the potential incremental benefits.

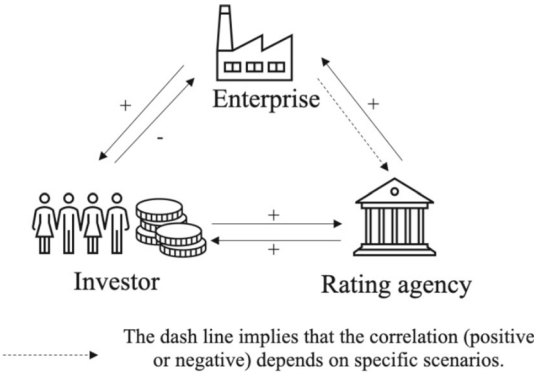

Fig. 2 Equilibrium strategy choices among tripartite players

5 Impact factor analysis and simulation

In this section, based on the replicator dynamic equations, we focus on analyzing the principal factors influencing the strategy choices of tripartite players, such as disclosure intensity, expected returns, and regulation strength. By doing so, we aim to provide theoretical evidence and numerical simulation that can inform the development of effective measures for the prevention of greenwashing behavior. MATLAB 2018a is employed to dynamically visualize this numerical experiment, drawing on initial values established in prior studies (Sun & Zhang, 2019; Liu et al., 2023), as presented in Table 6.

In addition to these parameters, we also set the initial values of x, y and z to vary from 0.1 to 1 with an evolutionary step of 0.2. Figure 3 displays the equilibrium state of the tripartite players' strategy portfolios and the corresponding evolutionary trajectories. The ESSs eventually stabilize on (1,1,1) for any initial state, which proves the validity of this simulation. In EGT, individual players in a population repeatedly interact, learn, and adapt their strategies over time, ultimately shaping the ESSs in a game (Taylor & Jonker, 1978). Thus, ESSs offer advantages to individuals using them compared to alternative strategies in terms of stability and non-invulnerability to intrusions from other strategies. In this case, as vividly shown in Fig. 3, the enterprise would choose the "FR" strategy, while the investor exhibits "Trust" in the "SE" strategy of the ESG rating agency.

5.1 Impact of external disclosure intensity (α_1,α_2) on the enterprise's strategy choices

Based on the replicator dynamics system of the enterprise, the first-order partial derivatives on disclosure intensity α_1, α_2 are listed as follows,

$$\frac{\partial F(x)}{\partial \alpha_1} = x(1-x)zP_1, \ \frac{\partial F(x)}{\partial \alpha_2} = x(1-x)(1-z)P_1$$

Hence,

Proposition 4 Enhancing the intensity of external disclosure would assist in curbing greenwashing while facilitating the enterprise's strategy evolution of "FR".

Proof 4 Based on the given assumptions that x, $z \in [0,1]$ and $P_1 > 0$, we can conclude that $F(x)$ is a monotonically increasing function concerning α_1 and α_2. As α_1 and α_2 increase,

Table 6 Initial values setting

Parameters	Initial values	Parameters	Initial values	Parameters	Initial values
I_2	5	I_3	10	P_1	40
ΔI_1	5	ΔI_3	10	P_2	40
α_1	0.8	α_2	0.5	I_5'	5
I_5	15	I_6	10	I_8	5
I_4	10	I_6'	10	I_8'	5
C_1	5	I_7	10	I_9	5
ΔC	5	C_2	5	β	0.8

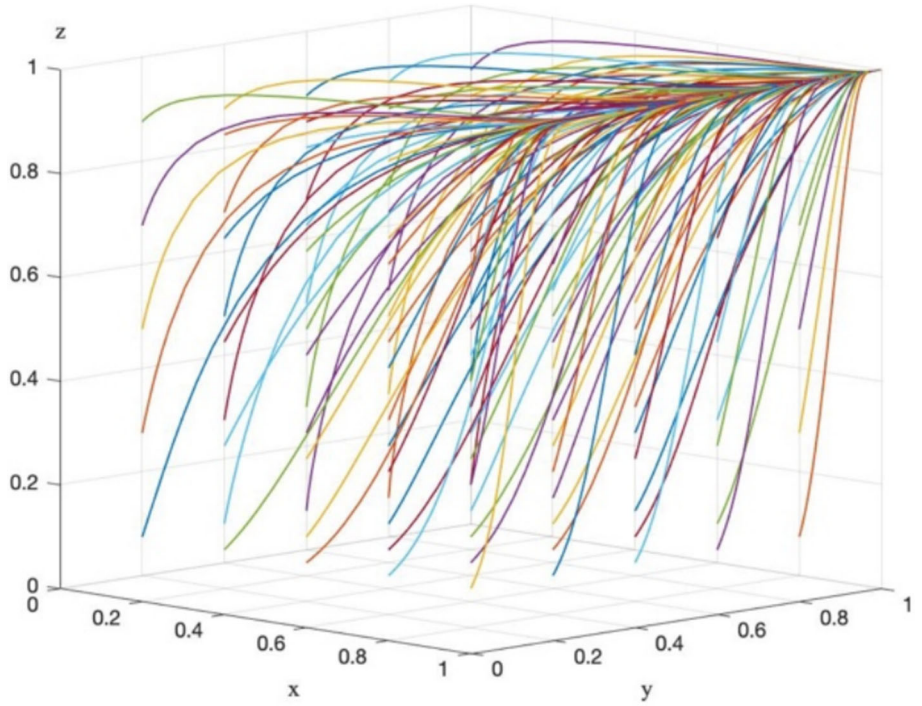

Fig. 3 ESSs results with evolutionary paths

$F(x)$ also increases. Consequently, the enterprise exhibits a stronger preference for choosing "FR" while displaying a diminishing willingness to choose "GW".

To simulate the impact paths of disclosure intensity α_1, focusing on the ESS results (1,1,1) shown in Fig. 3, we vary the value of α_1 at 0.7, 0.8, and 0.9 to depict the impact of α_1 fluctuations on the equilibrium strategy combinations and the enterprise strategy choice, as shown in Fig. 4a and b. While the evolutionary paths change with varying α_1 values, the ESSs of tripartite players remain at (1,1,1). In line with Proposition 4, it is found that α_1 is positively correlated with x. This result suggests that increased disclosure intensity facilitates the evolution of the enterprise's strategy towards "FR". Similar findings are evident in Fig. 4c and d, which illustrate that as α_2 increases, the share of the enterprise choosing "FR" also rises.

Consequently, irrespective of the strategy adopted by the ESG rating agency, imposing stricter disclosure requirements on the enterprise proves to be more effective in restraining greenwashing. Thus, regulators should prioritize establishing stringent institutional environments and industrial norms to expedite the enhancement of ESG disclosure intensity and curb the enterprise's misconduct (He et al., 2020; Hu et al., 2023). Additionally, increased public exposure and consumer whistle-blowing ability are not less valuable regulatory tools (Tian & Sun, 2022).

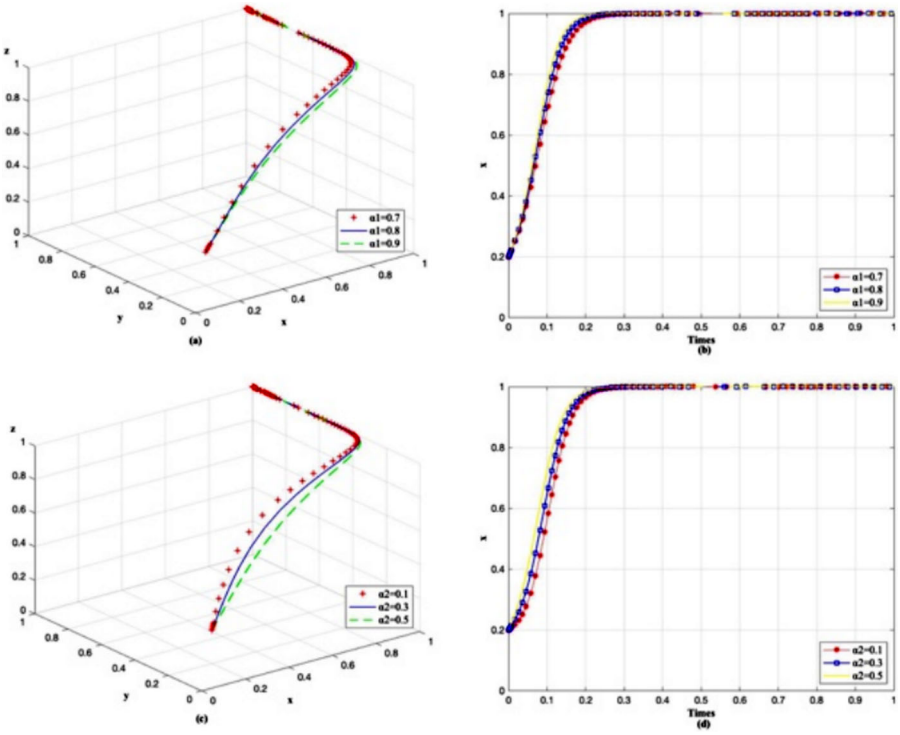

Fig. 4 Simulation of changing α_1, α_2

5.2 Impact of investors' professionalism and reliance returns (I_4, I_5) on their strategy choices

Likewise, we then examine the impact of returns derived from investors' professional judgment and reliance on ESG performance evaluated by the rating agency on investor's strategy choices. Using the replicator dynamics system, the first-order partial derivatives for I_4 and I_5 are presented as follows,

$$\frac{\partial F(y)}{\partial I_4} = -y(1-y), \ \frac{\partial F(y)}{\partial I_5} = y(1-y)[x + (1-x)z]$$

Hence,

Proposition 5 The returns from relying on the ESG rating agency would motivate the investor to choose the "Trust" strategy. Meanwhile, the individual professionalism induces the investor's choice of a "Distrust" strategy. Rating agencies faces the challenge from individual knowledge.

Proof 5 Based on the given assumptions that $x, y, z \in [0,1]$, we can observe the following relationships that, firstly, $F(y)$ is a monotonically increasing function of I_5, indicating that as I_5 increases, $F(y)$ also increases. This result implies that the investor is more likely to adopt the "Trust" strategy with a higher value of I_5. On the other hand, $F(y)$ is a monotonically decreasing function of I_4. As I_4 increases, $F(y)$ follows a decreasing pattern. Consequently,

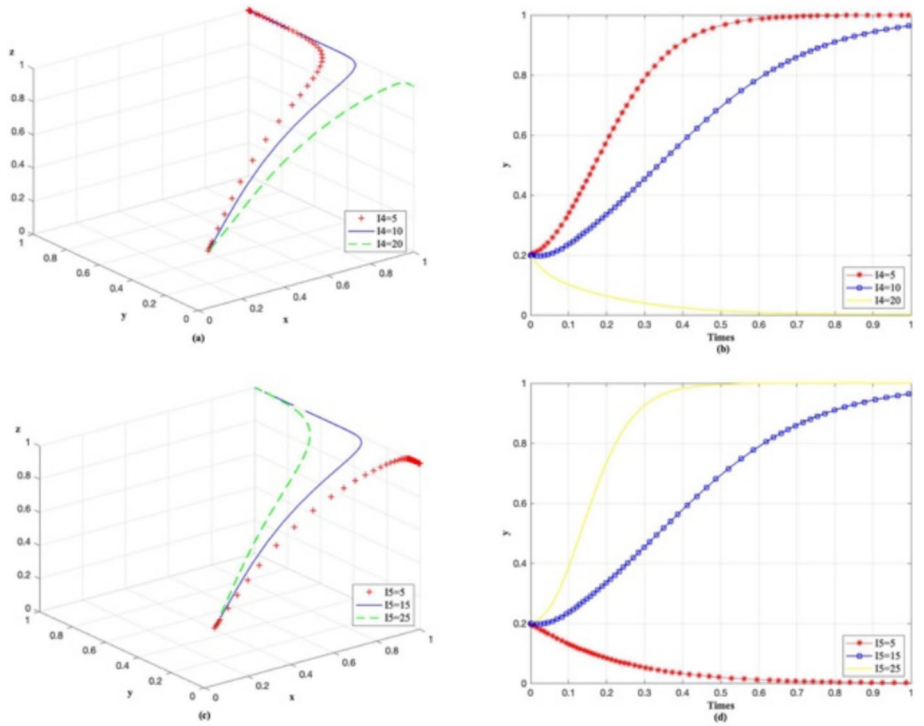

Fig. 5 Simulation of changing I_4, I_5

when I_4 is high, the investor will be more inclined to choose the strategy of "Distrust" rather than "Trust".

Given two scenarios of changing returns—I_4, I_5, this part aims to observe the evolutionary paths of the tripartite players' ESSs and the changes in the investor's strategy choices, based on the same settings presented in Fig. 3—ESS (1,1,1). Figure 5a illustrates that as I_4 increases from 5 to 10 and 20, the ESS transitions from (1,1,1) to (1,0,1), while Fig. 5b demonstrates a decreasing proportion of the investor choosing the "Trust" strategy with increasing I_4. These tendencies align with Proposition 5, suggesting that the rational profit-seeking investor with individual investment expertise may opt for more independent choices instead of trusting the rating agency.

However, when I_5 is changing from 5 to 15 and 25 (Fig. 5c), the ESS moves from (1,0,1) to (1,1,1). Simultaneously, the share that the investor choosing "Trust" is positively associated with I_5 (Fig. 5d). This result implies that when the ESG rating agency offers higher returns due to its expertise, it incentivizes the investor to choose the "Trust" strategy. In essence, bolstering investor trust through improvements in the professionalism of the rating agency and the delivery of superior expected investment returns is a crucial avenue for addressing the prevailing uncertainty obstacle of ESG ratings (Avramov et al., 2022). Coupled with the findings proposed in Proposition 2.2, a more transparent and reliable ESG rating system with an excess return instills investor confidence, facilitating the choice of "Trust" by the investors.

5.3 Impact of market returns (I_6, $I_6^{'}$, I_8, $I_8^{'}$), reputation returns (I_7, I_9), and regulation strength (β) on the rating agency's strategy choices

Regarding the factors influencing the strategy choice of the rating agency, the first-order partial derivatives of multi-sourced factors I_6, I_6', I_7, I_8, I_8', I_9, and β based on the replicator dynamics system are as follows,

$$\frac{\partial F(z)}{\partial I_6} = z(1-z)x,\ \frac{\partial F(z)}{\partial I_6'} = z(1-z)(1-x),\ \frac{\partial F(z)}{\partial I_7} = z(1-z)y$$
$$\frac{\partial F(z)}{\partial I_8} = -z(1-z)x,\ \frac{\partial F(z)}{\partial I_8'} = -z(1-z)(1-x),\ \frac{\partial F(z)}{\partial I_9} = -z(1-z)y$$
$$\frac{\partial F(z)}{\partial \beta} = z(1-z)P_2$$

Hence,

Proposition 6 The stringent regulation from external supervisors would enable the rating agencies to choose "SE", while the increasing market and reputation returns from enterprises and investors with "SE" would further motivate the rating agencies' strategy evolution to "SE". In contrast, these returns of the opposite strategy choice would hinder the option of "SE" for the rating agencies and lead to the selection of "NE".

Proof 6 According to the given assumptions that $x, y, z \in [0,1]$ and $P_2 > 0$, we can derive the results that $\frac{\partial F(z)}{\partial I_7} > 0$, $\frac{\partial F(z)}{\partial I_6} > 0$, $\frac{\partial F(z)}{\partial I_6'} > 0$, $\frac{\partial F(z)}{\partial \beta} > 0$, $\frac{\partial F(z)}{\partial I_9} < 0$, $\frac{\partial F(z)}{\partial I_8} < 0$, and $\frac{\partial F(z)}{\partial I_8'} < 0$. Thus, $F(z)$ increases with the increase in I_7, I_6, I_6', β, indicating a tendency for the rating agency to opt for the "SE" strategy. Yet, as I_9, I_8, and I_8' increase, $F(z)$ gradually decreases, suggesting a preference of the rating agency for the "NE" strategy.

Similarly, located in the equilibria (1,1,1) found in Fig. 3, the trajectories of the evolutionary paths in the scenarios of changing related returns of the rating agency from the enterprise $(I_6,\ I_6',\ I_7)$and the investor $(I_8,\ I_8',\ I_9)$, are depicted in Figs. 6, 7. Figure 6a–f shows that I_6, I_6', I_7 are positively related to z. An increase in the ESG rating agency's market returns and reputation returns from the "SE" strategy reinforces the agent's preference for maintaining high assessment standards. Conversely, as shown in Fig. 7a–f, I_8, I_8', and I_9 are negatively associated with z. These findings suggest that aligning the rating agency's financial and reputational interests with the accuracy and credibility of their ESG ratings could compel them to uphold the highest standards of rigor and transparency. This, in turn, would foster responsible ESG investments among investors, such as promoting genuine ESG-focused portfolios (Arvidsson & Dumay, 2022). Importantly, such efforts further help avoid the market dilemma of collusion between the rating agency and the enterprise.

Furthermore, we vary β as 0.1, 0.5, and 0.8 to explore the impacts of different external regulatory efforts. As shown in Fig. 8a, b, the findings reveal that β is positively correlated with z, aligning with the statement in Proposition 6. This result indicates that higher external regulation strength facilitates the ESG rating agency adopting the "SE" strategy. Consequently, regulators must take an active stance instead of remaining complacent (Tian & Sun, 2022). Implementing robust supervision and stringent regulations can avoid the occurrence of "general confusion" in ESG ratings conducted by rating agencies (Berg et al., 2022), which is a critical catalyst for greenwashing practices (Montgomery et al., 2023).

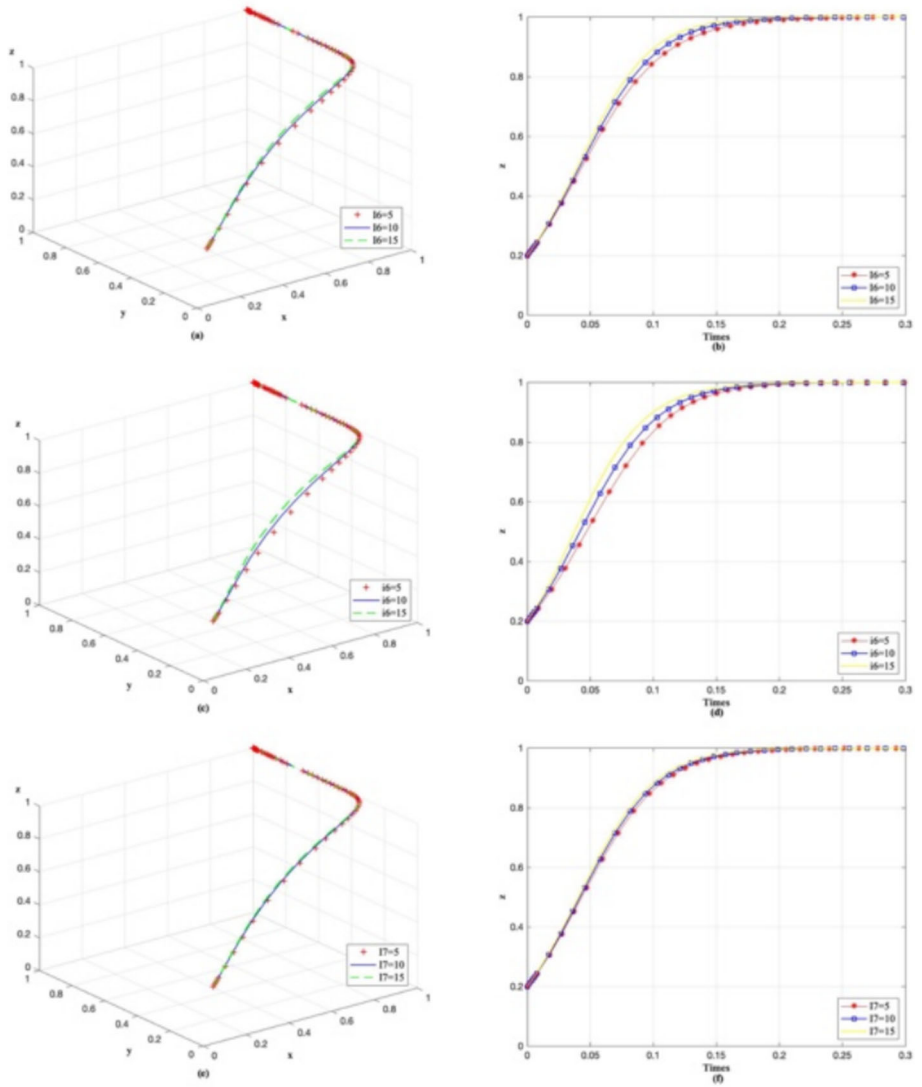

Fig. 6 Simulation of changing I_6, I_6', I_7

6 Conclusions and implications

The sustainable business process moves slower than expected (Nature, 2023). This sluggish progress is exacerbated by the prevalence of greenwashing behavior in ESG disclosure. While previous literature has predominantly emphasized the role of governmental regulations in addressing this issue, this study takes a game theory perspective to examine the behavior evolution mechanisms among multi-market agents: the enterprise, investor, and rating agency, and explore the market-government solutions to mitigate greenwashing practices.

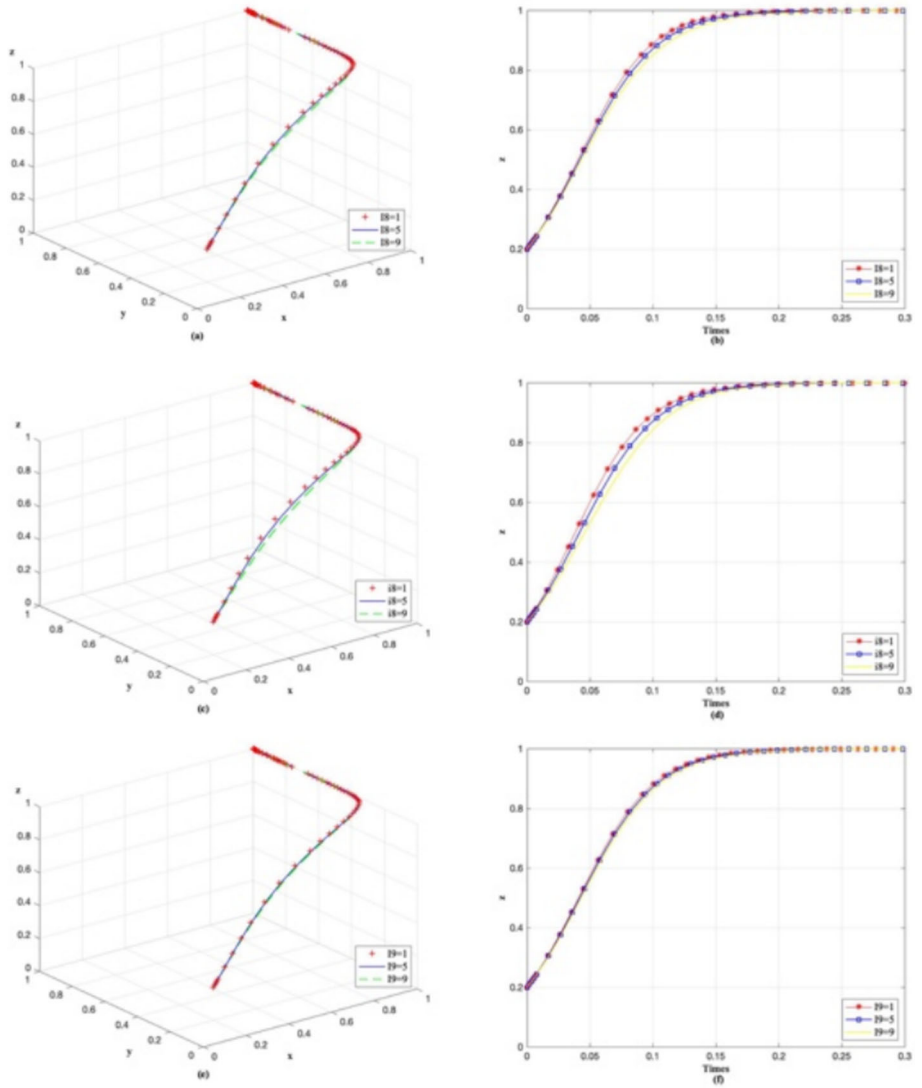

Fig. 7 Simulation of changing I_8, I_8', I_9

6.1 The end in sight of greenwashing—an ideal state

The critical findings highlight an ideal state of ESG disclosure characterized by pledge-keeping enterprises, faithful investors, and rigorous rating agencies under specific conditions. However, stakeholders should still be alert to the potential market dilemma in ESG disclosure—greenwashing by enterprises, questionable evaluations by rating agencies, and a crisis of investor confidence. This dilemma can be mitigated via the interactions among the tripartite players' strategy choices. For instance, strict evaluation by rating agencies can regulate enterprises' greenwashing behaviors, and honest reporting promotes investors' trust. In turn,

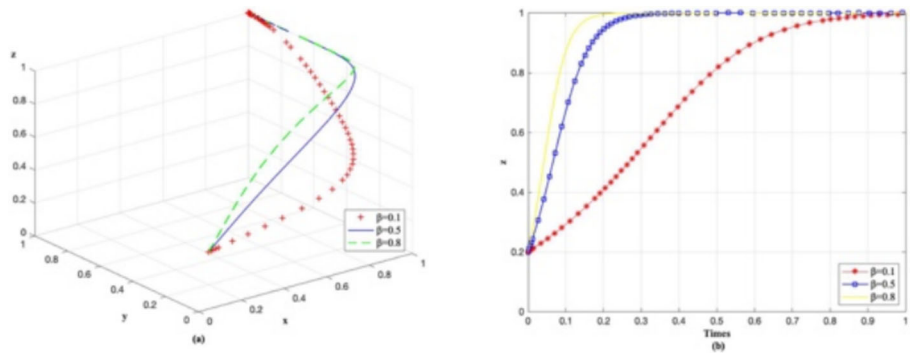

Fig. 8 Simulation results of changing β

this trust encourages rating agencies to adopt more rigorous evaluation practices, creating a mutually reinforcing cycle.

6.2 Essential mechanisms to curb greenwashing

6.2.1 Key stone: ESG rating agencies

The interaction analysis shows that the unbiased evaluations of ESG rating agencies can enhance investors' trust and reduce the intention of enterprises' greenwashing. Consequently, ESG rating agencies can be considered as a trigger to curb ESG greenwashing. By providing credible and transparent ESG assessments, rating agencies can enhance investor confidence in the integrity of ESG data and promote the adoption of genuine sustainability practices among enterprises (Li et al., 2023a, 2023b, 2023c). Conversely, if rating agencies fail to maintain high standards of evaluation, they risk eroding investor trust and inadvertently incentivizing enterprises to engage in greenwashing behaviors.

6.2.2 Multi-measures: external strict regulation and enhanced market and reputational returns

The analysis of the influence mechanisms reveals that regulatory intensity, along with market and reputational benefits, encourages rating agencies to adopt rigorous practices, thereby promoting fairness and transparency in ESG disclosure. To effectively curb greenwashing, it is essential to implement multiple measures that align stringent regulatory requirements with enhanced market-based and reputational incentives for rating agencies to maintain thorough ESG evaluations (Testa et al., 2018).

On the regulatory front, policymakers should mandate standardized ESG disclosure and impose penalties on rating agencies for inaccurate ratings. This requires agencies to uphold methodological rigor and transparency (Huang et al., 2023; Shan & Zhu, 2024). Complementing regulations, designing market-based mechanisms—such as setting benchmarks and market standards—should incorporate transparent disclosure methods and steps (Wang et al., 2023) and is expected to attract more attention from the stakeholders, in line with Teti et al. (2024)'s findings.

Specifically, leveraging reputational incentives can be effective. A public registry can recognize rating agencies demonstrating exemplary standards, while industry certification programs further incentivize credibility. Additionally, exposing agencies engaged in lax evaluation to media scrutiny can deter undesirable practices. This multi-pronged approach not only motivates enterprises to prioritize genuine sustainability over greenwashing but also restores investor confidence and drives meaningful progress toward an ideal equilibrium.

6.2.3 A policy instrument on enterprise side: mandatory ESG disclosure

Evidence from the analysis of influence mechanisms indicates that increased disclosure intensity directly curbs enterprises' greenwashing behavior. Echoing previous studies (He et al., 2020; Hu et al., 2023), strict disclosure is conducive to curb the enterprises' greenwashing behavior. Thus, mandatory disclosure could be considered as a powerful policy instrument to facilitate the transition from "deception" to "compliance" in ESG reporting.

One challenge, however, is that enterprises, especially those with poor ESG performance, may lobby against the introduction of stringent disclosure requirements. These entities often argue that compliance burdens are overly onerous or that regulations unfairly penalize certain industries. Compliance assistance and alternative incentives are needed to phase in requirements gradually. Furthermore, the enforcement of disclosure regulations requires dedicated monitoring and sanctioning regulators equipped with the necessary resources, expertise, and authority to effectively audit ESG reports. This ensures that enterprises adhere to the new standards and fosters a culture of accountability in ESG practices.

6.3 Theorical and practical significance

The research significance of this study covers the following two aspects. From the theoretical standpoint, focusing on the context of ESG disclosure and investment grounded in the evolutionary game theory, this study comprehends the dynamic decision-making mechanism of the central actors and unveils the formation process of non-compliance behavior of greenwashing within the ESG disclosure system. The findings herein clarify the effect of key actors and factors on enterprises' greenwashing behavior, enriching the dialogue between the ESG literature and game theory. The proposed analytical model, based on the innovative application of EGT, also provides a model basis for the follow-up research regarding ESG greenwashing. In terms of practical implications, this study highlights the crucial role of rating agencies' strict evaluation in mitigating greenwashing in ESG disclosure. It underscores the need for strong governance, with the power of government further strengthening ESG disclosure regulation, including disclosure methodology and details. More significantly, this study emphasizes that providing strong financial and reputational incentives to rating agencies could promote the entire system into a positive feedback loop, potentially hindering the prevalence of greenwashing.

6.4 Limitations and future work

This study has several limitations. First, we only consider the enterprises, investors, and rating agencies as the principal players to simplify the model analysis. Future studies may involve more stakeholders in the modeling work. Also, EGT has been developed by combining various approaches. Thus, future studies may center on the improved EGT approach, and then provide more interesting insights into curbing ESG greenwashing. In addition, this

study does not consider the heterogeneity within the same agent, such as the heterogeneity of scale and reputation among enterprise agents. What's more, a simulation analysis is adopted in this study, thus, the actual-data-based empirical study might be promising. Therefore, future work may start with these points to explore the regulation of greenwashing in ESG disclosure further.

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