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ESG Greenwashing Behaviour in the Electric Vehicle Supply Chain: Insights from evolutionary game theory

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Abstract **:**This study explores the governance of greenwashing behaviour within the Environmental, Social, and Governance (ESG) framework of the New Energy Vehicle (NEV) supply chain. Employing an evolutionary game theory model, we examine the strategic interactions between NEV Components Suppliers (NEVSs), NEV Manufacturers (NEVMs), and Government Regulatory Agencies (GRAs). We derive the conditions for evolutionarily stable strategies (ESS) and conduct sensitivity analysis to assess the impact of key factors on the evolution of optimal strategies. Our findings reveal the dynamic changes in ESG practices and greenwashing of supply chain enterprises under different market and regulatory environments. The results demonstrate that ESG practices in the supply chain exhibit distinct phased characteristics, transitioning from greenwashing behaviour in the initial stages to proactive ESG practices in the maturity stage. This research highlights the significant influence of market forces on companies' ESG strategic choices, suggesting that the government should implement appropriate regulatory and incentive strategies at different stages to guide enterprises from greenwashing towards authentic ESG practices. This study provides theoretical insights and practical guidance for policymakers and corporate strategists to promote sustainable development in the NEV industry.

Keywords: ESG Greenwashing; Governance; New Energy Vehicle; Supply Chain; Evolutionary Game.

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1. Introduction

With the rapid industrialization of society, the demand for energy has surged, leading to significant resource depletion and environmental degradation (Yuan et al., 2015; Zou et al., 2016). Research indicates that automobiles account for approximately 25% of global oil consumption, contribute to 80% of carbon emissions in the transportation sector (Yu et al., 2024). New Energy Vehicle (NEV), as green and clean modes of transportation, not only reduce dependence on traditional fossil fuels, but also lower carbon emissions in the transportation sector. This promotes a more sustainable direction for energy consumption (Das et al., 2024). Therefore, NEVs are considered a key driver in transforming the global energy structure.

In the context of global energy transformation, the importance of Environmental, Social, and Governance (ESG) principles has become increasingly evident (Lee & Lee, 2022). ESG practices help enterprises achieve sustainable development while addressing environmental challenges and improving corporate social responsibility and governance levels (Apergis et al., 2022; Yamoah et al., 2022). The development of NEV aligns closely with ESG principles, offering a natural advantage in promoting sustainable practices (Giri, 2019; Liu & Yu, 2020; Zhang & Cai, 2020;).

The importance of ESG practices in the NEV supply chain is becoming increasingly prominent. From the environmental (E) perspective, the NEV supply chain plays a significant role in realizing carbon neutrality goals. Research shows that the lifecycle carbon emissions of NEVs are 40-50% lower than traditional fuel vehicles, but this advantage largely depends on the greenness of the supply chain (Das et al., 2024). From the social (S) perspective, the NEV supply chain involves extensive labour and resource extraction and its social responsibility performance directly impacts the industry's reputation and sustainable development (Kraude & Narasimhan, 2024). In terms of governance (G), transparent corporate governance and efficient risk management are crucial for attracting investment and maintaining brand image (Asante-Appiah, 2020). Therefore, implementing comprehensive ESG practices in the NEV supply chain is significant for the long-term sustainable development of the industry and the realization of global environmental goals.

However, the NEV industry faces challenges such as policy uncertainties, fluctuating subsidies (Baars et al., 2020), technological hurdles (Hua et al., 2021), market competition pressures (Wang et al., 2020), and supply chain management (Sun et al., 2022; Gu et al., 2024). These challenges have led some companies to engage in greenwashing—making misleading claims about their environmental practices to reduce costs (Yu et al., 2020).

Greenwashing in the NEV supply chain manifests in diverse forms, posing significant challenges to industry integrity. Common greenwashing behaviours include subsidy fraud, exaggerated carbon reduction claims, and selective environmental information disclosure (Liao & Wu, 2024). These practices not only mislead consumers and stakeholders but also hinder sustainable development, exacerbating environmental pollution, resource waste, and social injustice (Liu & Li, 2024). Furthermore, they undermine genuine ESG efforts and negatively impact the industry's reputation and effectiveness in achieving sustainable development goals (Lee & Raschke, 2023).

Considering that the NEV supply chain involves multiple stakeholders, including GRAs NEVSs, and NEVMs, effective interaction and cooperation among these stakeholders are key to ensuring the authenticity and effectiveness of ESG practices (Wang et al., 2020). Governments can promote the development of NEVs and gain environmental benefits through policy support. Additionally, decisions regarding the production of NEVs must account for market dynamics, policy environments, and operational costs (Shi, 2020) adapting flexibly to rapid changes. Therefore, governments worldwide urgently need to implement effective governance against greenwashing behaviours to regulate ESG practices within the supply chain, ensuring sustainable development throughout production and sales processes.

Despite the growing importance of ESG practices in the NEV industry, there is a lack of research focusing on the dynamic interactions among stakeholders in ESG practices and greenwashing governance within this sector. This study aims to address this research gap by exploring the dynamic interactions between key stakeholders in the NEV supply chain and examining the evolution of corporate ESG practices and greenwashing behaviours under different market and regulatory environments. Our research contributes to the literature by providing a novel tripartite evolutionary game model that captures the complex interactions between these stakeholders, offering insights into effective governance strategies for promoting authentic ESG practices.

To address these issues, we pose three key research questions: (1) What are the main factors influencing ESG practice strategies within the NEV supply chain? (2) How can government policies be designed and implemented to effectively guide enterprises towards ESG practices? (3) What measures can effectively mitigate greenwashing behaviour in the NEV supply chain? We employ a tripartite evolutionary game model to analyze the strategic interactions among NEV component suppliers (NEVSs), NEV manufacturers (NEVMs), and government regulatory agencies (GRAs). Using Lyapunov's first law, we derive the conditions for Evolutionarily Stable Strategies (ESS) and conduct sensitivity analysis to assess the impact of key factors on the evolution of optimal strategies.

Our findings reveal the dynamic evolution of ESG practices and greenwashing behaviours under varying market and regulatory environments. The study shows that market sensitivity to environmental issues significantly impacts corporate ESG behaviour, underscoring the key role of market mechanisms in driving sustainable development. Governments should adopt appropriate regulatory and incentive strategies at different stages to promote green technology, reduce ESG costs for enterprises, and comprehensively regulate the supply chain. Finally, this article proposes phased government regulatory strategies to govern ESG greenwashing in the NEV supply chain.

Theoretically, this study pioneers the application of evolutionary game theory to the NEV industry, establishing an innovative tripartite evolutionary game model that reveals the dynamic interactions among g GRAs, NEVSs, and NEVMs.

This study contributes significantly to both theory and practice in ESG practices and greenwashing behaviours within the NEV supply chain. Theoretically, this study pioneers the application of evolutionary game theory to the NEV industry, establishing an innovative tripartite evolutionary game model that reveals the dynamic interactions among GRAs, NEVSs, and NEVMs. This model not only integrates market forces, regulatory pressures, and corporate strategies but also provides a dynamic framework for the evolution of ESG practices and greenwashing behaviours. Practically, the findings offer valuable guidance for policymakers in designing phased regulatory approaches and for businesses in adapting their ESG strategies to different industry development stages. This contributes to mitigating greenwashing behaviours, enhancing ESG practices, and ultimately promoting sustainable development in the NEV sector.

The remainder of this study is structured as follows: Section 2 reviews the literature to identify research gaps. Section 3 describes the construction process of the tripartite evolutionary game model. Section 4 analyzes the evolutionary stability strategy of the tripartite evolutionary game model. Section 5 presents the numerical simulation. Section 6 presents the discussion. The conclusions and policy implications are summarized in section 7.

2. Literature review

This section provides a comprehensive review of the existing literature on ESG practices and greenwashing in the NEV industry. It explores the unique characteristics of ESG implementation within the NEV supply chain, examines the various forms and impacts of greenwashing specific to this sector, and investigates the roles and interactions of key stakeholders. Through this analysis, we identify significant research gaps and highlight opportunities for future studies, particularly regarding governance strategies to address greenwashing in the NEV supply chain.

2.1 ESG practices in the NEV industry

The NEV industry, as a representative of green transportation, exhibits distinctive ESG practices. In terms of environmental (E) aspects, the NEV industry primarily focuses on reducing carbon emissions and improving energy efficiency. Studies demonstrate that NEVs significantly reduce lifecycle carbon emissions compared to conventional vehicles (Andersson & Börjesson, 2021). The industry is actively developing more efficient battery technologies and implementing closed-loop recycling systems to further enhance energy efficiency and mitigate environmental impacts(Liu et al., 2022; Xiong & Cheng, 2023; Xiao et al., 2024).

Regarding social (S) aspects, NEV companies contribute through employment generation, employee welfare improvement, and community engagement (Purcell et al., 2021; Zhang et al., 2024). Many NEVMs are addressing labour and environmental issues in the supply chain, such as ethical sourcing of materials and transitioning to more sustainable battery technologies (OFweek, 2021). In corporate governance (G), NEV companies are enhancing effectiveness by optimizing internal structures, increasing transparency, and strengthening risk management (Széchenyi István

University & Ercsey, 2016; Thomas, 2019).

2.2 Greenwashing behaviours and impacts

Despite the adoption of positive ESG practices, greenwashing in the NEV industry remains a significant concern. It stems from a complex interplay of factors, including policy uncertainties, high production and battery costs, technological hurdles, market competition pressures, evolving consumer expectations, and supply chain management challenges(Baars et al., 2020; Hua et al., 2021; Szabo & Webster, 2021; Sun et al., 2022; Gu et al., 2024).

These pressures often lead companies to engage in greenwashing practices, which manifest in various forms within the NEV industry(Williams, 2024). Common tactics include overstating the eco-friendliness of electric vehicles, neglecting full life-cycle assessments, misrepresenting raw material sourcing, particularly regarding conflict minerals in battery production (Kumar & Suresh, 2024); using vague "eco-friendly" terms, inflating recyclability claims, especially for batteries(Cremades & Casals, 2022); and understating the environmental impact of EV charging, particularly in fossil fuel-dependent regions (Rahman, 2021; Guzek et al., 2024).

These practices are widespread across the industry, affecting both leading NEV companies and traditional automakers. For instance, Land Rover, Toyota, Lexus, and Audi have been criticized for potentially exaggerating their vehicles' environmental benefits in advertisements (Hickman, 2021). Even Tesla, a leading NEV company, has faced environmental controversies, including regulatory violations, emissions control issues, and its removal from the S&P 500 ESG Index (Reuters, 2021; Financial Times, 2021; EPA, 2022). Wang (2024) employed AI models to detect Tesla's greenwashing behaviour, further illustrating the complexity of this issue in the NEV sector.

The impacts of greenwashing behaviours are significantly negative. Compared to genuine environmental actions, greenwashing lowers consumer reputation evaluations of companies (Du, 2015), misleads markets and consumers, and leads to inappropriate resource allocation (Lee & Raschke, 2023), undermines the implementation of carbon reduction measures (Liu & Yu, 2020; Baldi & Pandimiglio, 2022), and can lead to legal consequences (Cherry & Sneirson, 2012). In the NEV industry, greenwashing is particularly problematic as environmental attributes are a primary market selling point (Patala et al., 2019). If left unchecked, it will severely hinder the true sustainable development of the industry.

While the NEV industry demonstrates significant progress in ESG practices, the prevalence of greenwashing poses a substantial threat to its sustainable development. Therefore, it is crucial to govern ESG greenwashing behaviours within the supply chain and actively promote genuine sustainability efforts in the NEV sector.

2.3 Greenwashing governance

To address greenwashing, it is essential to explore efficient strategies to govern greenwashing. Existing studies primarily focus on external regulation and internal governance. From the perspective of external regulation, reducing greenwashing requires legislation and uniform international standards(Zhang, 2023a; Zhang et al., 2023). Studies have demonstrated that sustainability ratings, government penalty mechanisms, and rigorous scrutiny by media and NGOs can effectively curb corporate greenwashing (Parguel et al., 2011; Zhang, 2023b; Seele & Gatti, 2017; Tan & Zhu, 2022). For internal governance, increasing the number of independent directors and institutional investors, establishing robust environmental management systems, and implementing independent environmental audit can effectively curb corporate greenwashing (Lyon & Maxwell, 2011; Yu et al., 2020; Chen et al., 2024). However, most studies analyze greenwashing governance from a single perspective, neglecting the interaction and cooperation among stakeholders (Dhaliwal et al., 2014; Tsang, 2023). There is a lack of research on industry-specific governance strategies that account for the unique challenges of the NEV sector.

2.4 Evolutionary game model and ESG research

ESG practices involve dynamic interactions among multiple stakeholders (Dhaliwal, 2014; Das et al., 2024). Previous ESG research has primarily focused on its performance and economic outcomes. These studies have mostly employed systematic literature reviews, quantitative methods (e.g., panel data models and regression analyses), case studies, content analysis of company reports and disclosures, and comparative studies across industries and countries (Friede et al., 2015; Ashwin Kumar et al., 2016; Savio et al., 2023). While these approaches have provided valuable insights, they are limited in capturing the dynamic process of ESG practice, particularly within the continuous interaction and evolution of multiple stakeholders (Alam et al., 2019; Naseer et al., 2023; Tsang, 2023). This study adopts evolutionary game theory to address these limitations.

The evolutionary game model, which combines traditional game theory with dynamic evolutionary processes, has been widely applied in economics, environmental studies, and logistics (Friedman, 1991; Liu et al., 2021; Wu et al., 2024). It offers several advantages in analyzing ESG practices and greenwashing behaviours in the NEV supply chain. This approach enables the examination of strategy evolution over time, reflecting the adaptive nature of firm behaviour (Friedman, 1991). It also incorporates bounded rationality, aligning with real-world decision-making processes in complex environments (Weibull, 1997). Moreover, it allows for analysis at the population level of firms, providing insights into industry-wide dynamics and the emergence of dominant strategies (Nowak et al., 2004). The concept of evolutionarily stable strategies (ESS) facilitates the identification of long-term equilibria and their stability (Smith, 1982). Additionally, it helps reveal complex interactions between enterprises, governments, and other stakeholders (Liu et al., 2023; Zhang et al., 2024).

The dynamic nature of the NEV industry, characterized by rapidly changing technology, regulations, and market demands, makes evolutionary game theory an ideal approach for studying ESG practices and greenwashing behaviours among its diverse stakeholders. By employing evolutionary game theory, this study aims to provide a more comprehensive and dynamic understanding of ESG practices and greenwashing behaviours in the NEV supply chain, addressing gaps in existing research and offering new insights for both theoretical development and practical applications for effective governance strategies.

2.5 Research gap

In summary, despite the increasing research on ESG in recent years, there is a lack of focus on the dynamic interactions among stakeholders in ESG practices. Additionally, studies specifically addressing ESG practices and greenwashing governance within the NEV industry remain relatively scarce. Significant differences in greenwashing governance measures across industries highlight a clear deficiency in industry-specific governance methods. Therefore, it is crucial to conduct in-depth studies on greenwashing governance strategies tailored to the stakeholders in the NEV industry. By introducing the evolutionary game model, this study explores how various factors influence the strategic choices of GRAs, NEVSs, and NEVMs. It provides new perspectives and methods for ESG practice and greenwashing governance. Our research offers theoretical foundations and practical guidance for policy-making and corporate strategy formulation, aiming to address the unique challenges of greenwashing in this sector, ultimately enhancing the credibility and effectiveness of

ESG practices and achieving genuine sustainable development in the NEV industry.

3. Evolutionary game model analysis

3.1 Model description

In the face of intense market competition, enterprises in the supply chain must choose between high-cost ESG practices and lower-cost greenwashing strategies. We suppose that divergent strategies among upstream and downstream enterprises may lead to risks such as partner loss and reputational damage for those engaging in greenwashing. Besides, if all entities within the supply chain adopt greenwashing, collusive behaviour may emerge, significantly hindering the industry's sustainable development. Conversely, if all enterprises choose ESG practices, the entire supply chain can achieve sustainable development.

The government, as a regulatory entity, plays a decisive role in promoting ESG practices and preventing greenwashing behaviours. Through the enactment and stringent enforcement of environmental regulations, the government can foster genuine ESG compliance and deter companies from making superficial environmental claims. Insufficient regulatory enforcement may lead companies to opt for the lower cost greenwashing strategy of the NEV industry, ultimately undermining the environmental integrity and market credibility. Therefore, the government must carefully balance maintaining stringent environmental standards with promoting industry development.

This study categorizes government regulatory strategies into stringent and lenient types. This division reflects two extreme scenarios of government regulatory intensity in the NEV sector, ranging from strict to lenient (Xia et al., 2024). This binary classification captures regulatory trends and enables the simulation of market reactions across policy cycles. By comparing outcomes under different regulatory intensities, we provide a basis for dynamic strategy formulation. This approach, widely adopted in similar studies (Li & Gao, 2022; Zou et al., 2023; Zhao et al., 2024), enhances the comparability and consistency of research findings across the field.

In summary, this study constructs a two-tier supply chain comprising NEVSs and NEVMs, employing a tripartite evolutionary game model to analyze the dynamic behaviours and strategic interactions among stakeholders from a supply chain perspective. The focus is on how government regulatory policies can guide ESG practices and govern greenwashing behaviour in the supply chain. This approach aims to develop comprehensive analytical methods and incentive policies to prevent potential collusive greenwashing. Fig. 1 illustrates the strategic interactions among stakeholders within the NEV supply chain.

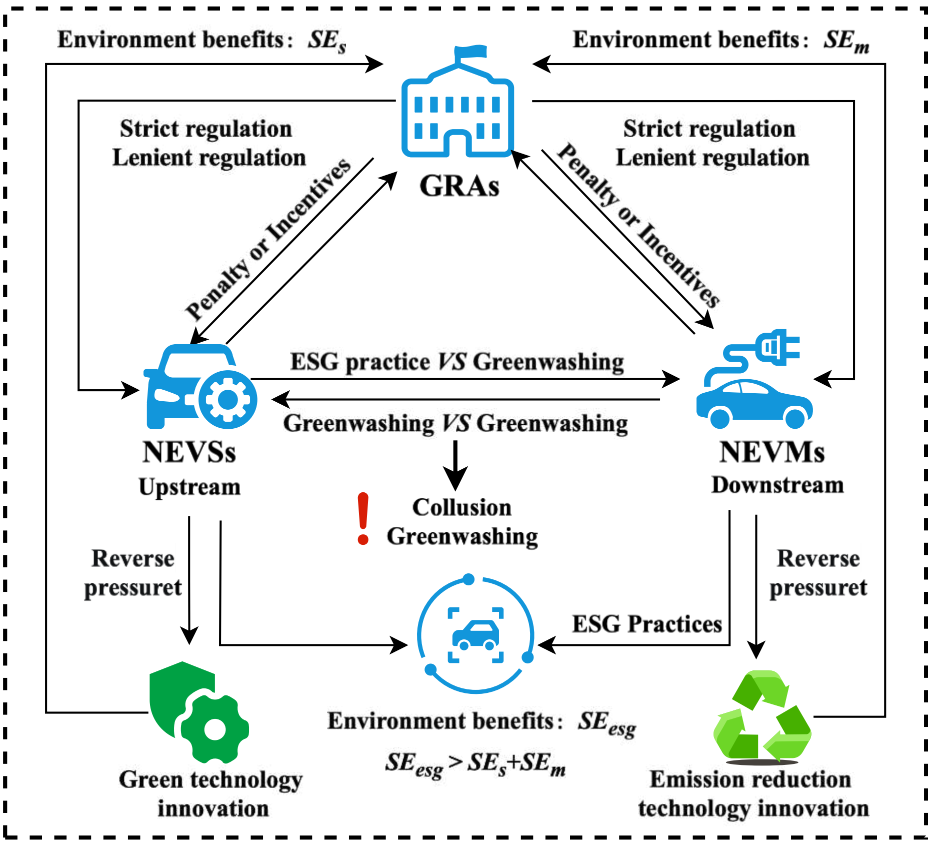

Fig. 1. The game relationship between Governments, NEVSs and NEVMs.

3.2 Model assumptions and parameter settings

(1) Behavioural strategies of participants in evolutionary game

In the evolutionary game, each participant is assumed to be boundedly rational, aiming to maximise its own utility through two pure strategies. Specifically, the strategy set for NEVSs is N_1 ={ESG Practices(x), Greenwashing(1-x)}. Similarly, the strategy set for NEVMs is N_2 ={ESG practices(y), Greenwashing(1-y)}. The strategy set for GRAs is N_3 ={Strict regulation(z), Lenient regulation(1-z)}. Where $x(t), y(t), z(t) \in [0,1]$ are all probabilities functions of time t. Throughout the game, Players continuously adjust strategies based on repeated trials and observations, converging to optimal strategies over time.

(2) Parameter settings

To facilitate the modeling, we make the following assumptions are made based on the behavioral strategies of the participants to describe the benefits and costs for NEVSs, NEVMs, and GRAs. Table 1 shows the specific parameter symbols and their meanings.

For NEVSs and NEVMs, we denote basic production and manufacturing costs as C_s and C_m, and basic revenues as R_s and R_m, respectively. When choosing ESG practices, enterprises need to incur additional costs (ΔC_s for NEVSs, ΔC_m for NEVMs) due to increased production and manufacturing expenses, R&D costs, and operating and advertising costs. Similarly, these practices also generate additional revenues (ΔR_s for NEVSs, ΔR_m for NEVMs). Greenwashing involves speculative costs (C_{ss} for NEVSs, C_{ms} for NEVMs) and potential reputational losses (L_s, L_m).

When the strategies of NEVSs and NEVMs are different, e.g., if NEVSs chooses to greenwash while NEVMs choose ESG practices, NEVSs suffer reputational damage L_s and the cost of lost customers R_{pl}. Conversely, if NEVMs choose to greenwash while NEVSs adopt ESG practices, the NEVSs are indirectly affected, though they have already mitigated some reputational risk through their ESG practices. To quantify this, we introduce a reputational risk coefficient R_{sc} to measure the indirect impact of greenwashing on reputation. This is quantified as $R_{sc}L_m$ for NEVMs and $R_{sc}L_s$ for NEVSs, representing the indirect reputational impact of one party's greenwashing on the other.

We assume that the additional costs of ESG practices are greater than the speculative costs of greenwashing, i.e., $\Delta C_s > C_{ss}$ and $\Delta C_m > C_{ms}$. We introduce risk coefficients R_{pl} to represent the risk of losing partners, R_{mr} to measure market sensitivity to greenwashing, and R_{sc} to quantify the indirect impact on supply chain reputation.

When both NEVSs and NEVMs adopt greenwashing strategies, collusive greenwashing can occur, providing short-term benefits such as cost savings (C_{co}) from reduced compliance costs or shared investments. We assume that $C_{co} < \Delta C_s$ and $C_{co} < \Delta C_m$. Collusive greenwashing can also yield market advantages, resulting in additional revenues R_{co}.

The regulatory costs for GRAs are represented by C_g for strict regulation and θC_g for lenient regulation, where $\theta \in [0,1]$. Under strict regulation, firms engaged in greenwashing face penalties (P_s, P_m), while those adhering to ESG practices receive rewards(B_s, B_m). The environmental benefits of ESG practices are represented as SE_s and SE_m when adopted individually by NEVSs or NEVMs, respectively. When the entire supply chain implements ESG practices, the resulting environmental benefit is denoted as SE_{esg}. Notably, $SE_{esg} > SE_s + SE_m$, which captures the synergistic effects inherent in sustainable supply chains. When both NEVSs and NEVMs implement ESG practices, it enables better supply chain integration, optimizing resource use and processes (Gunasekaran et al., 2015), facilitates comprehensive life cycle management (Ostojic & Traverso, 2024), spurs joint innovations (Tian & Shi, 2024) and create economies of scale in sustainable practices (Samuel et al., 2021). These synergies potentially yield greater environmental benefits than the sum of individual efforts, supporting our assumption that $SE_{esg} > SE_s + SE_m$.

Table 1

Model parameter descriptions

Game player	Symbol	Parameter description
NEVSs	C_s, ΔC_s	The basic production cost and extra cost for ESG practices of NEVSs.
	R_s, ΔR_s	The basic revenue and extra revenue from ESG practices of NEVSs.
	L_s	Loss of reputation for NEVSs due to greenwashing.
	C_{ss}	Speculative cost for NEVSs.
NEVMs	C_m, ΔC_m	The basic production cost and extra cost for ESG practices of NEVMs.
	R_m, ΔR_m	The baseline revenue and extra revenue from ESG practices of NEVMs.
	L_m	Loss of Reputation due to greenwashing for NEVMs.
	C_{ms}	Speculative cost for NEVMs.
Supply Chain Shared Parameters	C_{co}	Cost savings from collusive greenwashing.
	R_{co}	Extra revenue from collusive greenwashing.
	R_{pl}	The potential loss incurred by the greenwashing party due to the increased likelihood of losing supply chain partners.
	R_{mr}	Market reaction coefficient, measuring sensitivity to greenwashing.
	R_{sc}	Reputation risk coefficient that indicates indirect impact on supply chain reputation ($R_{sc} \in [0,1]$).
GRAs	C_g	The cost of strict supervision by government regulators.
	θ	The cost of coefficient of loose supervision by government regulators ($\theta \in [0,1]$).
	B_s, B_m	The rewards of government for NEVSs and NEVMs practising ESG.
	P_s, P_m	The penalties imposed by the government on NEVSs and NEVMs practising greenwashing.
	SE_s, SE_m	Environmental benefits to the government from the ESG practices of NEVSs and NEVMs, respectively.
	SE_{esg}	Environmental benefits to the government from entire supply chain ESG practices.
	C_E	The damage to the environment caused by supply chain greenwashing.

Given these assumptions and parameters, the three-party evolutionary game model for the NEV supply chain yields eight strategy combinations. Table 2 presents the resulting payoff matrix.

Table 2

The payoff matrix for the tripartite game

NEVSs	NEVMs	GRAs	
		Strict Regulation (z)	Lenient Regulation $(1-z)$
ESG (x)	ESG (y)	$R_s + \Delta R_s - C_s - \Delta C_s + B_s$ $R_m + \Delta R_m - C_m - \Delta C_m + B_m$	$R_s + \Delta R_s - C_s - \Delta C_s$ $R_m + \Delta R_m - C_m - \Delta C_m$

		$SE_{esg} - C_g - B_s - B_m$	$SE_{esg} - \theta C_g$
	Greenwashing $(1-y)$	$R_s + \Delta R_s - C_s - \Delta C_s + B_s - R_{sc}L_s$ $R_m - C_m - P_m - L_m - C_{ms} - R_{pl} - R_{mr}R_m$ $SE_s - C_g - B_s + P_m$	$R_s + \Delta R_s - C_s - \Delta C_s - \theta R_{sc}L_s$ $R_m - C_m - L_m - C_{ms} - \theta R_{pl} -$ $\theta R_{mr}R_m$ $SE_s - \theta C_g$
Greenwashing $(1-x)$	ESG (y)	$R_s - C_s - P_s - L_s - C_{ss} - R_{pl} - R_{mr}R_s$ $R_m + \Delta R_m - C_m - \Delta C_m + B_m - R_{sc}L_m$ $SE_m - C_g + P_s - B_m$	$R_s - C_s - L_s - C_{ss} - \theta R_{pl} - \theta R_{mr}R_s$ $R_m + \Delta R_m - C_m - \Delta C_m - \theta R_{sc}L_m$ $SE_m - \theta C_g$
	Greenwashing $(1-y)$	$R_s - C_s - P_s - L_s - C_{ss} - R_{mr}R_s + C_{co} + R_{co}$ $R_m - C_m - P_m - L_m - C_{ms} - R_{mr}R_m + C_{co} +$ R_{co} $P_s + P_m - C_g - C_E$	$R_s - C_s - L_s - C_{ss} + C_{co} + R_{co} -$ $\theta R_{mr}R_s$ $R_m - C_m - L_m - C_{ms} + C_{co} + R_{co} -$ $\theta R_{mr}R_m$ $-\theta C_g - C_E$

4. Evolutionary stability analysis

4.1 Construction of replicator dynamics equations

For NEVSs, the payoff functions for adopting the ESG practices strategy and the greenwashing strategy are denoted as U_{11} and U_{12} respectively. Thus, we have the following equation:

$$U_{11} = \Delta R_s - \Delta C_s - C_s + R_s + B_s z - [\theta(1 - y - z + yz) + z(1 - y)]L_s \tag{1}$$

$$U_{12} = (1 - y)(R_{co} + C_{co}) - C_s - C_{ss} - L_s + R_s - P_s z - [\theta(1 - z) + z]R_{mr}R_s - [\theta y(1 - z) + yz]R_{pl} \tag{2}$$

The average expected payoff function for NEVSs, U_1, is calculated as: $U_1 = xU_{11} + (1 - x)U_{12}$.The replicator dynamics equation, which is a differential equation representing the growth rate of probability over time, for NEVSs is given by:

$$F(x) = \frac{dx}{dt} = x[U_{11} - U_1] = x(1 - x)\big[C_{ss} - C_{co} - \Delta C_s + \Delta R_s + L_s - R_{co} - \theta L_s R_{sc} + \theta R_{mr}R_s + \big(C_{co} + R_{co} + \theta L_s R_{sc} + \theta R_{pl}\big)y + (B_s + P_s + (1 - \theta)(R_{mr}R_s - L_s R_{sc}))z + (1 - \theta)(R_{pl} + L_s R_{sc})yz\big] \tag{3}$$

Similarly, the replicator dynamics equations for NEVMs and GRAs can be derived as follows:

$$F(y) = \frac{dy}{dt} = y[U_{21} - U_2] = y(1 - y)\big[C_{ms} - C_{co} - \Delta C_m + \Delta R_m + L_m - R_{co} - \theta(L_m R_{sc} - R_{mr}R_m) + \big(C_{co} + R_{co} + +\theta(L_m R_{sc} + R_{pl})\big)x + (B_m + P_m - (\theta - 1)(L_m R_{sc} + R_{mr}R_m))z + (1 - \theta)(R_{pl} + L_m R_{sc})xz\big] \tag{4}$$

$$F(z) = \frac{dz}{dt} = z[U_{31} - U_3] = z(z - 1)\big[(1 + \theta)C_g - P_m - P_s + (B_s + P_s)x + (B_m + P_m)y\big] \tag{5}$$

Here, U_{21} and U_{22} represent the payoff functions for NEVMs when adopting ESG practices and greenwashing strategies, respectively. Similarly, U_{31} and U_{32} denote the payoff functions for GRAs when implementing strict and lenient regulation strategies, respectively. Detailed formulas and derivations for these functions are provided in Appendix A.

4.2 Analysis of game evolution path

This section analyses the evolutionary stability strategies of NEVSs, NEVMs, and GRAs.

4.2.1 Evolutionary stability analysis of NEVSs

The stability of the replicator dynamics equation for NEVSs must satisfy $F(x) = 0$ and $dF(x)/dx < 0$. At this point, x is the evolutionary stable point for NEVSs. Based on equation (1), we obtain:

$$\frac{dF(x)}{dx} = (1 - 2x)(A_1 + B_1 y + C_1 z + D_1 yz) \tag{6}$$

Where $A_1 = C_{ss} - C_{co} - \Delta C_s + \Delta R_s + L_s - R_{co} - \theta(L_s R_{sc} - R_{mr} R_s)$, $B_1 = \big(C_{co} + R_{co} + \theta(L_s R_{sc} + R_{pl})\big)$, and $C_1 = B_s + P_s - (1 - \theta)(L_s R_{sc} + R_{mr} R_s)$, $D_1 = (1 - \theta)(R_{pl} + L_s R_{sc})$. To further simplify the analysis, we let $I(z) = (A_1 + B_1 y + C_1 z + D_1 yz)$.

If $0 < z = z^* = \frac{-A_1 - B_1 y}{C_1 + D_1 y} < 1, I(z^*) = 0$, and $F(x) = 0$ is always satisfied, this indicates that the game system is in a stable state, as shown in Fig. 2(a). The surface in the figure divides the strategy space into two regions, I and II, with the ESS of the supply chain on the shaded surface. This implies that if the probability of strict government regulation is fixed at z^*, the probability of ESG practice among NEVSs in the supply chain is uncertain but stable. If $0 < z < z^* = \frac{-A_1 - B_1 y}{C_1 + D_1 y} < 1, I(z) < 0$, then $F'(0) < 0, F'(1) > 0$. In this case, $x^* = 0$ is the ESS, corresponding to the replicator dynamics equation shown in Fig. 2(b). Here, the initial state of the NEVSs is in region II of the strategy space, and they will eventually choose greenwashing. If $0 < z^* = \frac{-A_1 - B_1 y}{C_1 + D_1 y} < z < 1, I(z) > 0$, then$F'(0) > 0, F'(1) < 0$. In this scenario, $x^* = 1$is the ESS, corresponding to the replicator dynamics equation shown in Fig. 2(c). Here, the initial state of NEVSs is in region I of the strategy space, and they will ultimately choose ESG practices.

4.2.2 Evolutionary stability analysis of NEVMs

The stability analysis for the replicator dynamics equation for NEVMs must satisfy $F(y) = 0$ and $dF(y)/dy < 0$. At this point, y is the evolutionary stable point for NEVMs. Based on equation (2), we derive:

$$\frac{dF(y)}{dy} = (1-2y)(A_2 + B_2x + C_2z + D_2xz) \quad (7)$$

Where $A_2 = C_{ms} - C_{co} - \Delta C_m + \Delta R_m + L_m - R_{co} - \theta(L_m R_{sc} - R_{mr} R_m)$, $B_1 = C_{co} + R_{co} + \theta(L_m R_{sc} + R_{pl})$, and $C_1 = B_m + P_m + (1-\theta)(R_{mr}R_m - L_m R_{sc})$, $D_1 = (1-\theta)(R_{pl} + L_m R_{sc})$. To further simplify the analysis, we let $J(z) = (A_2 + B_2x + C_2z + D_2xz)$.

If $0 < z = z^* = \frac{-A_2 - B_2x}{C_2 + D_2x} < 1, J(z^*) = 0$,and $F(y) = 0$ is always satisfied, this indicates that the game system is in a stable state, as shown in Fig. 2(d). The shaded area in the figure divides the strategy space into two regions, I and II, with the ESS of the supply chain located on the shaded area. This implies that if the probability of strict government regulation is fixed at z^*, the probability of ESG practice among NEVSs in the supply chain is uncertain, but stable. If $0 < z < z^* = \frac{-A_2 - B_2x}{C_2 + D_2x} < 1, J(z) < 0$,then $F'(0) < 0, F'(1) > 0$. In this case, $y^* = 0 =$ 0 is the ESS, corresponding to the replicator dynamics equation shown in Fig. 2(e). Here, the initial state of NEVMs is in region II of the strategy space, and they will eventually choose greenwashing. If $0 < z^* < z < 1, J(z) > 0$,then $F'(0) > 0, F'(1) < 0$. In this scenario, $y^* = 1$ is the ESS, corresponding to the replicator dynamics equation shown in Fig. 3(f). Here, the initial state of NEVMs is in the region I of the strategy space, and they will eventually choose ESG practices.

4.2.3 Evolutionary stability analysis of GRAs

The stability of the replicator dynamics equation for the government must satisfy $F(z) = 0$ and $dF(z)/dz < 0$. At this point, z is the evolutionarily stable point for the government. Based on equation (3), we derive: $dF(z)/dz = (2z-1)\left[(1+\theta)C_g - P_m - P_s + (B_s + P_s)x + (B_m + P_m)y\right]$. Let $K(x) = (1+\theta)C_g + P_s(x-1) + P_m(y-1) + B_sx + B_my$, when $x^* = \frac{[P_s + P_m - C_g - \theta C_g - (B_m + P_m)y]}{(B_s + P_s)}$, $K(x) = 0$.

If $0 < x = x^* < 1, K(x^*) = 0$, and $F(z) = 0$ is always satisfied, this indicates that the game system is in a stable state, as shown in Fig. 2(g). The shaded area in the figure divides the strategy space into two regions, I and II, with the government's ESS located on the shaded area. This implies that if the probability of ESG practice by NEVSs is fixed at x^*, the probability of the government choosing strict regulation is uncertain, but stable. If $0 < x < x^* < 1$, and $K(x) < 0$,then $F'(0) >$

$0, F'(1) < 0$. In this case, $z^* = 1$ is the ESS, corresponding to the replicator dynamics equation shown in Fig. 2(h). Here, the initial state of the government is in region I of the strategy space, and it will eventually choose the strict regulation strategy. If $0 < x^* < x < 1$, and $K(x) > 0$, then $F'(0) < 0, F'(1) > 0$. In this scenario, $z^* = 0$ is the ESS, corresponding to the replicator dynamics equation shown in Fig. 2(i). Here, the initial state of the government is in region II of the strategy space, and it will eventually choose the lenient regulation strategy.

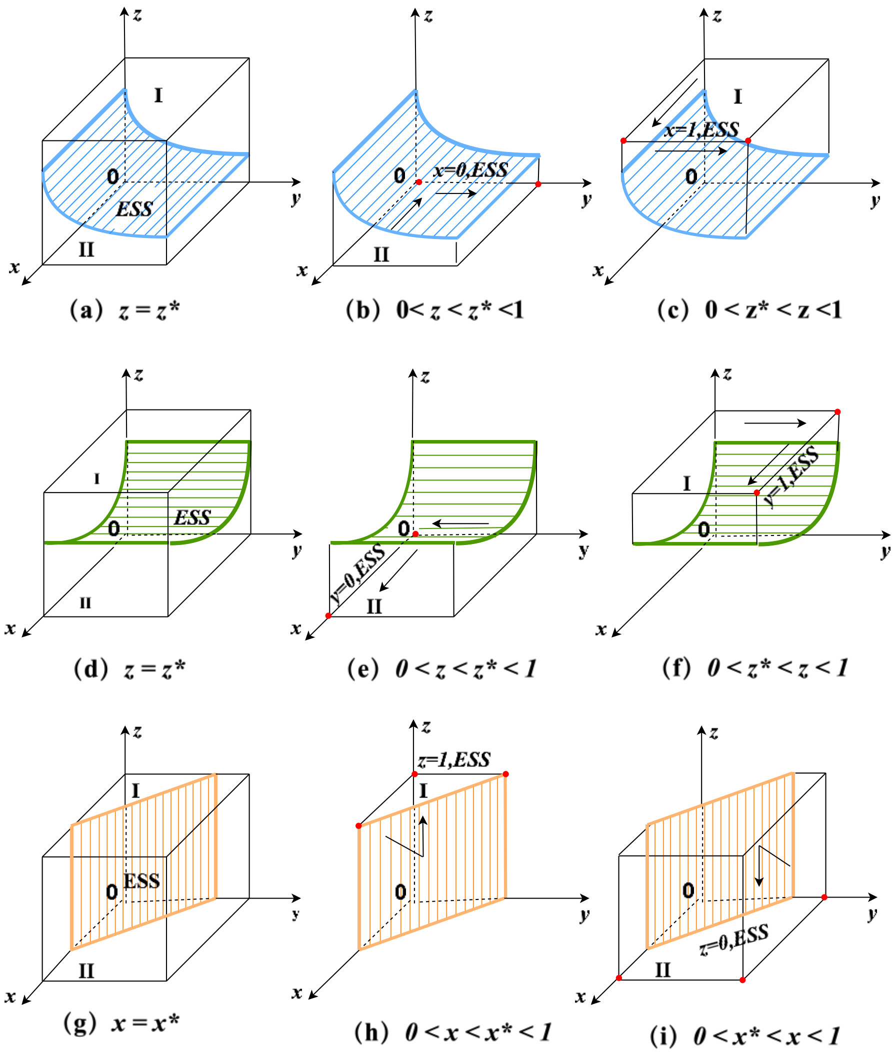

Fig. 2. Dynamic evolution path of NEVSs, NEVMs, GRAs strategies.

4.3 System stability analysis

Based on the above analysis, the equation system $F(x), F(y), F(z)$ is constructed into a three-dimensional dynamic system $F(x, y, z)$:

$$
\begin{cases}
F(x) = x(1-x)\begin{bmatrix} C_{ss} - C_{co} - \Delta C_s + \Delta R_s + L_s - R_{co} - \theta L_s R_{sc} + \theta R_{mr} R_s + \left(C_{co} + R_{co} + \theta L_s R_{sc} + \theta R_{pl}\right)y \\ +(B_s + P_s + (1-\theta)(R_{mr}R_s - L_s R_{sc}))z + (1-\theta)(R_{pl} + L_s R_{sc})yz \end{bmatrix} \\
F(y) = y(1-y)\begin{bmatrix} C_{ms} - C_{co} - \Delta C_m + \Delta R_m + L_m - R_{co} - \theta(L_m R_{sc} - R_{mr} R_m) + \left(C_{co} + R_{co} + +\theta\left(L_m R_{sc} + R_{pl}\right)\right)x \\ +\left(B_m + P_m - (\theta - 1)(L_m R_{sc} + R_{mr} R_m)\right)z + (1-\theta)(R_{pl} + L_m R_{sc})xz \end{bmatrix} \\
F(z) = z(z-1)\left[(1+\theta)C_g - P_m - P_s + (B_s + P_s)x + (B_m + P_m)y\right]
\end{cases} \tag{8}
$$

Setting $F(x, y, z) = 0$ yields 8 pure strategy equilibrium points (E_1 to E_8), as ESS exists only in pure strategies (Friedman, 1991). These points represent the dynamic evolutionary equilibrium strategies. According to Lyapunov's first law, a local equilibrium point is confirmed to be gradually stable only if all the eigenvalues of the Jacobian matrix of the system are negative. The eigenvalues of each equilibrium point are calculated, as shown in Table 3. The Jacobian matrix is:

$$
J = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z} \\ \frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z} \end{bmatrix} \tag{9}
$$

Table 3

Jacobian matrix eigenvalues corresponding to each equilibrium point.

Equilibrium Point	λ_1	λ_2	λ_3	stability
(0,0,0)	$P_m - C_g + P_s + \theta C_g$	$C_{ms} - C_{co} - \Delta C_m + \Delta R_m + L_m - R_{c0} - \theta L_m R_{sc} + \theta R_m R_{mr}$	$C_{ss} - C_{co} - \Delta C_s + \Delta R_s + L_s - R_{c0} - \theta L_s R_{sc} + \theta R_s R_{mr}$	Conditional ESS
(1,0,0)	$P_m - C_g - B_s + \theta C_g$	$C_{ms} - \Delta C_m + \Delta R_m + L_m + \theta R_{pl} + \theta R_m R_{mr}$	$C_{co} - C_{ss} + \Delta C_s - \Delta R_s - L_s + R_{c0} + \theta L_s R_{sc} - \theta R_s R_{mr}$	Conditional ESS
(0,1,0)	$P_s - C_g - B_m + \theta C_g$	$C_{ss} - \Delta C_s + \Delta R_s + L_s + \theta R_{pl} + \theta R_s R_{mr}$	$C_{co} - C_{ms} + \Delta C_m - \Delta R_m - L_m + R_{c0} + \theta L_m R_{sc} - \theta R_m R_{mr}$	Conditional ESS
(0,0,1)	$C_g - P_m - P_s - \theta C_g$	$B_m - C_{co} + C_{ms} - \Delta C_m + \Delta R_m + L_m + P_m - R_{c0} + R_m R_{mr} - L_m R_{sc}$	$B_s - C_{co} + C_{ss} - \Delta C_s + \Delta R_s + L_s + P_s - R_{c0} + R_s R_{mr} - L_s R_{sc}$	Conditional ESS
(1,0,1)	$B_s + C_g - P_m - \theta C_g$	$B_m + C_{ms} - \Delta C_m + \Delta R_m + L_m + P_m + R_{pl} + R_m R_{mr}$	$C_{co} - B_s - C_{ss} + \Delta C_s - \Delta R_s - L_s - P_s + R_{c0} - R_s R_{mr} + L_s R_{sc}$	Conditional ESS
(0,1,1)	$B_m + C_g - P_s - \theta C_g$	$B_s + C_{ss} - \Delta C_s + \Delta R_s + L_s + P_s + R_{pl} + R_s R_{mr}$	$C_{co} - B_m - C_{ms} + \Delta C_m - \Delta R_m - L_m - P_m + R_{c0} - R_m R_{mr} + L_m R_{sc}$	Conditional ESS
(1,1,0)	$\theta C_g - B_s - C_g - B_m$	$\Delta C_m - C_{ms} - \Delta R_m - L_m - \theta R_{pl} - \theta R_m R_{mr}$	$\Delta C_s - C_{ss} - \Delta R_s - L_s - \theta R_{pl} - \theta R_s R_{mr}$	Conditional ESS
(1,1,1)	$B_m + B_s + C_g - \theta C_g$	$\Delta C_m - C_{ms} - B_m - \Delta R_m - L_m - P_m - R_{pl} - R_m R_{mr}$	$\Delta C_s - C_{ss} - B_s - \Delta R_s - L_s - P_s - R_{pl} - R_s R_{mr}$	instability

By analyzing the eigenvalues of the Jacobian matrix yields five key propositions. Through system stability analysis, this study aligns the five propositions with different stages of ESG development in the NEV industry, demonstrating the evolution of corporate behaviours strategies at each stage, as shown in Table 4.

Table 4

Stability conditions of equilibrium points.

Equilibrium Point	Stability Conditions	Proposition	Stage
(0,0,0)	$P_s \downarrow, P_m \downarrow, \Delta C_s \uparrow, \Delta C_m \uparrow, R_{c0} \uparrow, C_{co} \uparrow$	*Proposition 1*	Initial
(1,0,0)	$P_s \sim, P_m \sim, \Delta C_s \sim, \Delta R_s \uparrow, \Delta C_m \sim, R_{c0} \sim, C_{co} \sim$	*Proposition 2*	Transitional
(0,1,0)	$P_s \sim, P_m \sim, \Delta C_s \sim, \Delta R_m \uparrow, \Delta C_m \sim, R_{c0} \sim, C_{co} \sim$	*Proposition 2*	Transitional

(0,0,1)	$P_s\uparrow, P_m\uparrow, \Delta R_s < \Delta C_s, \Delta R_m < \Delta C_m$	*Proposition 3*	Transitional
(1,0,1)	$P_m\uparrow, B_s\downarrow, \Delta C_s\sim, \Delta C_m\sim, \Delta R_s\uparrow, \Delta R_m\sim, R_{c0}\sim, C_{co}\sim$ $\Delta(\Delta R_s - \Delta C_s)\uparrow$	*Proposition 3*	Transitional
(0,1,1)	$P_s\uparrow, B_m\downarrow, \Delta C_s\sim, \Delta C_m\sim, \Delta R_s\sim, \Delta R_m\uparrow, R_{c0}\sim, C_{co}\sim$ $\Delta(\Delta R_m - \Delta C_m)\uparrow$	*Proposition 4*	Transitional
(1,1,0)	$\Delta R_s > \Delta C_s; \Delta R_m > \Delta C_m$	*Proposition 5*	Mature

Note *: ↑ means the value increases, ↓ means the value decreases, ~ means the value keeps the same, and $\Delta(\Delta - \Delta)$ means the differential difference.*

***Proposition* 1:** When $C_g - (P_m + P_s) > \theta C_g, \Delta R_s - \Delta C_s - \theta L_s R_{sc} < R_{c0} - (C_{ss} - C_{co}) - L_s - \theta R_s R_{mr}, \Delta R_m - \Delta C_m - \theta L_m R_{sc} < R_{c0} - (C_{ms} - C_{co}) - L_m - \theta R_s R_{mr}$, the corresponding evolutionarily stable strategy is {Greenwashing, Greenwashing, Lenient Regulation}, denoted as $E_1(0,0,0)$.

This proposition indicates that when the cost of strict regulation is significantly high for GRAs and the penalties for greenwashing by NEVSs and NEVMs are relatively low, the GRAs tend to adopt a lenient regulatory strategy, while companies opt for greenwashing to reduce costs and rapidly increase market competitiveness. This scenario typically occurs in environments lacking effective regulation and market pressure, as illustrated in Fig. 3(a). For policymakers, it emphasizes the need to establish regulatory mechanisms, particularly in the industry's early stages. For companies, this underscores the importance of prioritizing long-term sustainability over short-term cost-saving, given the dynamic nature of regulatory and market environments in maturing industries.

***Proposition* 2:** When $C_g + B_s - P_m > \theta C_g, \Delta R_s - \Delta C_s - \theta L_s R_{sc} > R_{c0} - (C_{ss} - C_{co}) - L_s - \theta R_s R_{mr}, \Delta R_m - \Delta C_m < -(C_{ms} + L_m + \theta R_{pl} + \theta R_m R_{mr})$, the evolutionary stable strategy is {ESG Practices, Greenwashing, Lenient Regulation}, denoted as $E_2(1,0,0)$.

This proposition suggests that as ESG investment concepts deepen, even under lenient government regulation, NEVSs may opt for voluntary ESG information disclosure. The benefits of this will outweigh the indirect impact of greenwashing by supply chain partners, resulting in a mixed strategy where NEVSs choose ESG Practices. The evolutionary result is shown in Fig. 3(b). Similarly, when $P_s - C_g - B_m < -\theta C_g$, $\Delta R_s - \Delta C_s < -(C_{ss} + L_s + \theta R_{pl} + \theta R_s R_{mr})$, $\Delta R_s - \Delta C_s < -(C_{ss} + L_s + \theta R_{pl} + \theta R_s R_{mr})$, and $\Delta R_m - \Delta C_m - \theta L_m R_{sc} > R_{c0} - (C_{ms} - C_{co}) - L_m - \theta R_m R_{mr}$, the equilibrium point $E_3(0,1,0)$ is the ESS, corresponding to the evolutionarily stable strategy {Greenwashing, ESG Practices, Lenient Regulation}.

This finding implies that market forces can drive ESG adoption even under lenient government regulation. For policymakers, this suggests complementing direct regulation with strategies to nurture market demand for ESG practices, such as enhancing consumer environmental awareness through public education and transparent information disclosure. For companies, proactive ESG adoption may confer competitive advantages, particularly in environmentally conscious markets. However, firms must also remain vigilant about potential reputational impacts from their supply chain partners' behaviours.

***Proposition* 3:** When $(P_m + P_s) - C_g > -\theta C_g$, $\Delta R_m - \Delta C_m + B_m - L_m R_{sc} < R_{c0} - (C_{ms} - C_{co}) - L_m - P_m - R_m R_{mr}$, $\Delta R_s - \Delta C_s + B_s - L_s R_{sc} < R_{c0} - (C_{ss} - C_{co}) - L_s - P_s - R_s R_{mr}$, the corresponding evolutionarily stable strategy is {Greenwashing, Greenwashing, Strict Regulation}, denoted as $E_4(0,0,1)$.

This proposition indicates that under strict regulation, the total revenue from penalties exceeds that from lenient regulation, prompting the government to adopt a strict regulatory strategy. However, due to policy implementation lag, the economic benefits of ESG practices remain lower than the economic incentives for collusive greenwashing, leading stakeholders in the supply chain to tend towards collusive greenwashing. The evolutionary outcome of this scenario is illustrated in Fig. 3(c). This finding reveals the potential unintended effects of stringent regulation, where firms may engage in collective deception if ESG costs outweigh greenwashing risks. For policymakers, this suggests complementing punitive measures with incentives to reduce ESG implementation costs. For corporations, it emphasizes cultivating supply chain-wide transparency and integrity to prevent collective deceptive practices.

***Proposition* 4:** When $(B_s + C_g) - P_m > \theta C_g, \Delta R_s - \Delta C_s - L_s R_{sc} + B_s > R_{c0} - (C_{ss} - C_{co}) - L_s - P_s - R_s R_{mr}$, and $\Delta R_m - \Delta C_m < -(B_m + C_{ms} + L_m + P_m + R_{pl} + R_m R_{mr})$, the corresponding evolutionarily stable strategy is {ESG Practices, Greenwashing, Strict Regulation}, denoted as $E_5(1,0,1)$.

Proposition 4 indicates that under strict government regulation, NEVSs opt for ESG practices due to higher benefits, while NEVMs may choose to greenwash if ESG costs are excessive. In this case, the equilibrium point $E_5(1,0,1)$ is the ESS, corresponding to the evolutionarily stable strategy {ESG Practices, Greenwashing, Strict Regulation}. Similarly, when $\theta C_g > (B_m + C_g) - P_s$, $\Delta R_s - \Delta C_s < -(B_s + C_{ss} + L_s + P_s + R_{pl} + R_s R_{mr})$, and $\Delta R_m - \Delta C_m - L_m R_{sc} + B_m > R_{c0} - (C_{ms} - C_{co}) - L_m - P_m - R_m R_{mr}$, the equilibrium point $E_6(0,1,1)$ is the ESS, corresponding to the evolutionarily stable strategy {Greenwashing, ESG Practices, Strict Regulation}. The evolutionary outcome of this scenario is depicted in Fig. 3(d). For policymakers, it suggests tailoring regulations to specific segments, potentially offering more support for those with higher ESG implementation costs. For businesses, this highlights the critical importance of supply chain collaboration. ESG practices adopted by upstream entities may create both pressures and opportunities for downstream counterparts. Consequently, firms need to develop comprehensive supply chain ESG strategies.

***Proposition* 5:** When $\theta C_g < C_g + (B_s + B_m), \Delta R_m > \Delta C_m, \Delta R_s > \Delta C_s$, the corresponding evolutionarily stable strategy is {ESG Practices, ESG Practices, Lenient Regulation}, i.e., $E_7(1,1,0)$.

This proposition delineates an ideal state where the entire supply chain voluntarily adopts ESG practices under moderate regulation. Due to the continuous strict regulation in the previous stage, the risk of greenwashing in the supply chain increases, reducing the extra cost savings and economic incentives from collusive greenwashing. Concurrently, strict regulation coupled with rewards and subsidies for ESG practices has stimulated supply chain entities to improve green innovation technologies, thereby reducing the costs of ESG practices. The evolutionary outcome of this scenario is illustrated in Fig. 3(e). For policymakers, this suggests that the ultimate regulatory goal should be to nurture a self-disciplined industry ecosystem. A gradual transition from strict regulation to market-oriented incentive mechanisms can be considered. For businesses, this highlights the importance of integrating ESG practices into core operations. Companies should focus on innovations that reduce ESG implementation costs and develop business models where these practices create economic value.

Based on the above analysis, $E_7(1,1,0)$ represents an ideal state where NEVSs and NEVMs can effectively self-regulate under the government's lenient regulation strategy. In this state, the entire supply chain actively adheres to ESG principles without engaging in greenwashing practices. In conclusion, these five propositions collectively illustrate the dynamic evolution of ESG practices in the NEV industry supply chain. They demonstrate a progression from an initial state of widespread greenwashing (Proposition 1) through various transitional stages (Propositions 2-4) to a mature state of voluntary ESG adoption (Proposition 5). This evolution is driven by the interplay of regulatory pressures, market forces, and changing cost-benefit dynamics of ESG practices. Policymakers are advised to adopt a nuanced approach that combines regulatory mechanisms with market-oriented incentives, while businesses are encouraged to view ESG practices as a long-term strategic imperative rather than a mere compliance issue.

5. Numerical simulation

5.1 System evolution trajectory simulation

This section validates the theoretical results and analysis of Section 3 through numerical simulation experiments. Based on the replicator dynamics equations and ESS conditions, MATLAB R2022a is used to simulate the dynamic strategy evolution paths of stakeholders and explore the impact of various factors on their decision-making. To ensure the reasonableness of the numerical examples, the model parameter values are calibrated based on relevant literature parameters (Table 5) (Zheng et al., 2023; Liu et al., 2023; Zhang et al., 2024).

Table 5

Parameter settings for different ESS scenarios.

Parameter	Array 1	Array 2	Array 3	Array 4	Array 5
$\boldsymbol{\Delta C_s}$	70	20	80	80	50
$\boldsymbol{\Delta R_s}$	50	50	50	50	60
$\boldsymbol{\Delta C_m}$	70	20	80	50	50
$\boldsymbol{\Delta R_m}$	50	5	50	60	60
$\boldsymbol{C_g}$	10	20	30	30	20
$\boldsymbol{P_s}$, $\boldsymbol{P_m}$	2	2	20	20	2
$\boldsymbol{R_{co}}$, $\boldsymbol{C_{co}}$	10	10	5	5	3

Setting the initial probabilities of (x, y, z) to $(0.5, 0.5, 0.5)$, the evolution paths of arrays 1-5 are shown in Fig. 3(a)-(e). All x, y, z curves converge to different ESS points. System simulation is used to model and observe the system's evolutionary behaviour of the system under specific parameter conditions, while sensitivity analysis further explores the impact of parameter changes on system behaviour. By combining these two methods, we can gain a more comprehensive understanding of the dynamic process of ESG practices in the supply chain and how to promote sustainable development by adjusting key parameters. Therefore, the following sensitivity analysis aims to further explore the impact of different factors on the ESS.

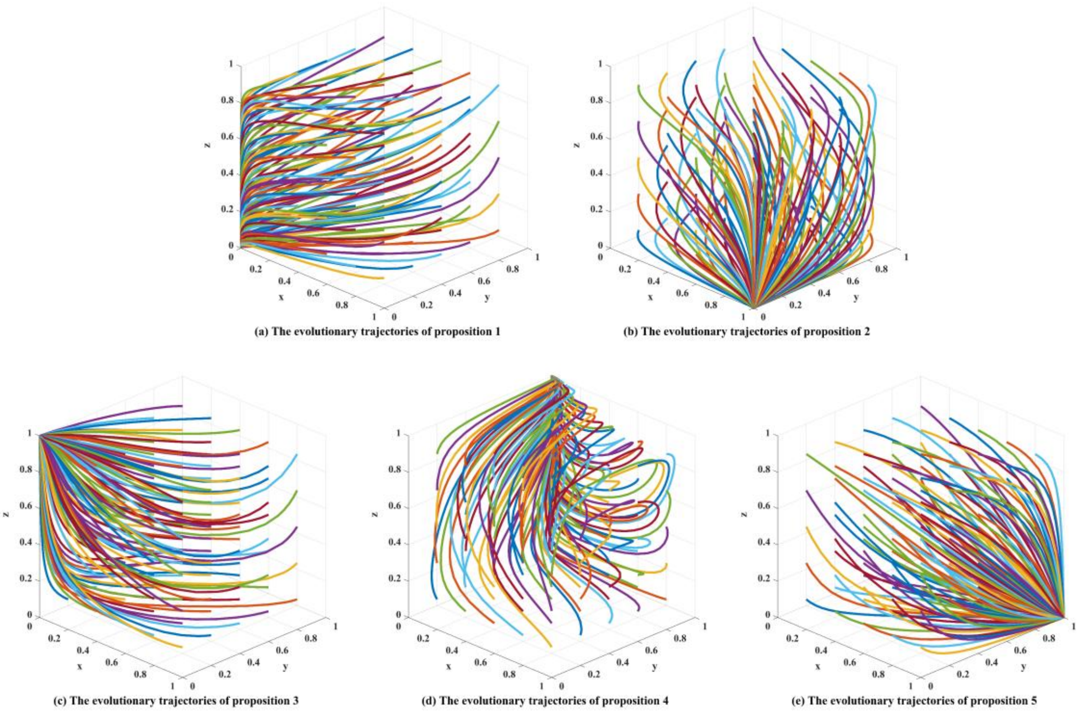

Fig. 3. Evolutionary paths of the tripartite game

5.2 Sensitivity analysis

5.2.1 Single-factor sensitivity analysis

In this section, the primary influencing factors selected include the cost savings of collusive greenwashing (C_{co}), the benefits of collusive greenwashing (R_{co}), the costs of supplier ESG practices (ΔC_s), the costs of NEVMs ESG practices (ΔC_m). These factors are used to explore the evolutionary characteristics of the system. Based on the previous analysis, our goal is to achieve the strategy combination $E_7(1,1,0)$ by promoting the participants in the evolutionary game. Therefore, the initial values of the relevant parameters are consistent with Table 5.

(1) The cost savings of collusive greenwashing

The cost savings of collusive greenwashing mainly refer to the expenses saved by enterprises in avoiding compliance costs. For example, companies might save on operating and maintenance costs by not investing in environmental technology or facilities, or they might reduce procurement costs by using cheaper materials and production processes with lower environmental standards. To study the impact of different C_{co} on the strategy choices of the three parties in the supply chain under $E_7(1,1,0)$, different cost savings C_{co} are set to $(5,15,25,35,45)$. Fig. 4 shows the simulation results for different C_{co} settings.

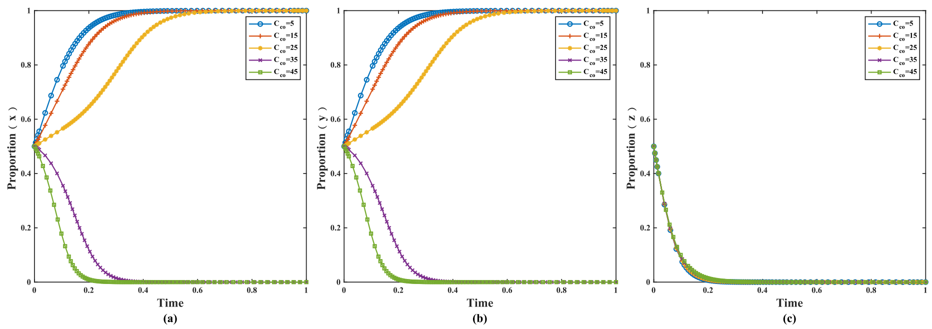

Fig. 4. Evolutionary results under different C_{co}

In Fig. 4(a)-(b), when $C_{co} \leq 25$, the speed at which x and y converge to 1 gradually slows down as C_{co} increases; when $C_{co} > 25$, the speed of convergence accelerates, and x and y converge to 0. This indicates that the supply chain tends to adopt greenwashing behaviour as C_{co} increases. Fig. 4(c) shows that the probability z of the government's strict regulation strategy increases slowly with C_{co}. This may be because the government recognizes the increase in greenwashing behaviour and attempts to curb this trend by strengthening regulation. However, the slow growth rate of z indicates that the government's efforts to enhance regulation do not keep pace with the increase in greenwashing behaviour by NEVSs and NEVMs, possibly due to a regulatory lag, which prevents the government from fully curbing collusive greenwashing behaviour. This finding highlights the need for companies to carefully weigh short-term gains against long-term risks of greenwashing. Policymakers should create stronger regulations to make greenwashing costs exceed its benefits, encouraging genuine ESG practices.

(2) The benefits of collusive greenwashing

When collusion within the supply chain involves greenwashing, enterprises typically gain direct financial benefits by reducing environmental investments. The extra benefits of collusive greenwashing are mainly reflected in two aspects: firstly, reducing environmental investments reduces production costs, increasing marginal profits in the short run; secondly, under lenient regulation, violating environmental regulations allows enterprises to produce at lower costs, gaining market competitiveness through price reductions. To describe the impact of the additional benefits of collusive greenwashing R_{co} on the strategy choices of the three parties in the supply chain under $E_7(1,1,0)$, R_{co} is set to $(5,15,25,35,45)$. Fig. 5 shows the simulation results for different R_{co} settings.

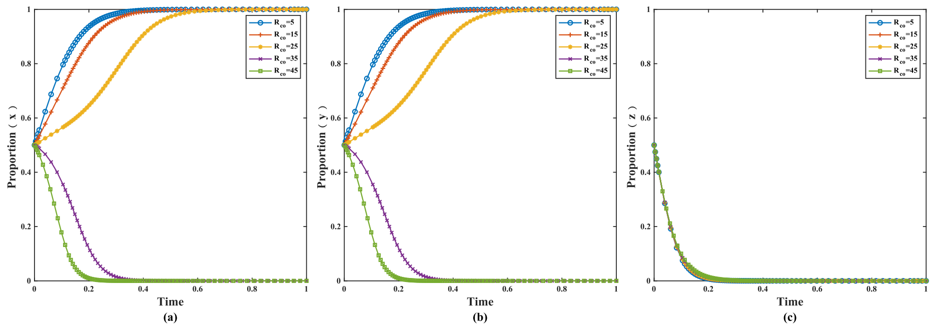

Fig. 5. Evolutionary results under different R_{co}

As shown in Fig. 5, as R_{co} increases, enterprises in the supply chain are more inclined to adopt greenwashing strategies, while the probability of government regulation decreases, although the rate of decline is relatively slow. This may reflect a real-world situation, under the lure of high benefits, other participants in the supply chain might forsake environmental responsibility, and although the government attempts to maintain regulation, the regulatory effort may be insufficient to completely prevent greenwashing behaviour. In this scenario, corporate decision-makers must recognize that while greenwashing may offer short-term gains, it potentially jeopardizes long-term business sustainability and reputation. Concurrently, it is necessary to strengthen policy incentives and regulatory measures to effectively curb greenwashing behaviour in the supply chain and promote genuine ESG practices.

(3) The ESG practice costs in the supply chain

To describe the impact of the ESG practice costs ΔC_s and ΔC_m on the strategy choices of the three parties under the condition $E_5(1,1,0)$, ΔC_s and ΔC_m are set to (10, 15, 20, 30, 40). Fig. 6-7 show the simulation results for different practice cost settings.

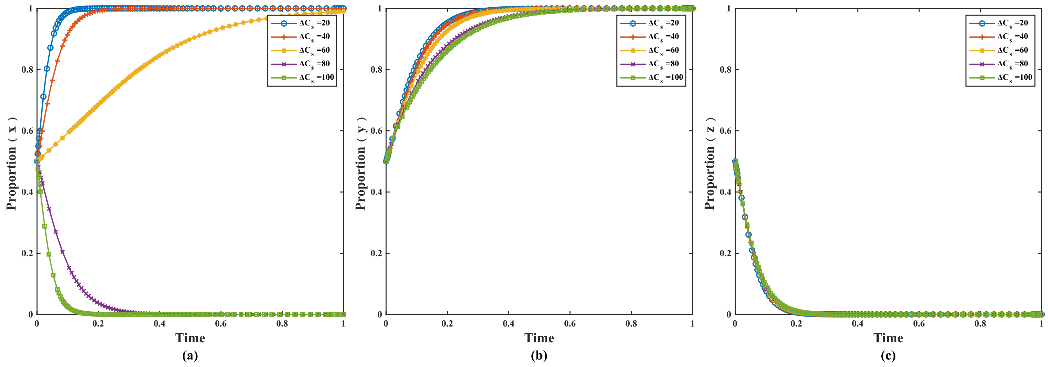

Fig. 6. Evolutionary results under different ΔC_s

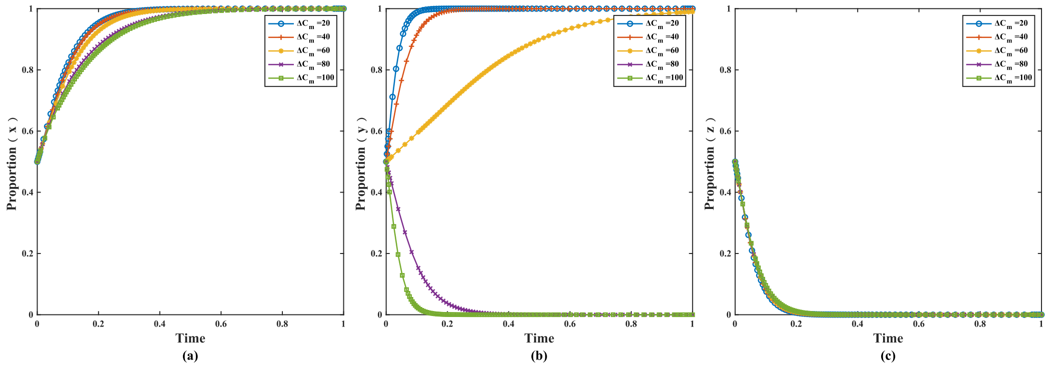

Fig. 7. Evolutionary results under different ΔC_m

As shown in the figures, when the cost of ESG practice in the supply chain increases, the probability of choosing ESG practice strategies decreases significantly for both upstream and downstream supply chain participants. This impact is more pronounced for the party experiencing the cost increase and has cascading effects on the strategic decisions of its supply chain partners. These findings underscore the imperative for businesses to prioritize cost-efficient ESG implementation strategies. Policymakers and businesses should collaborate to balance cost pressures and maintain the momentum for sustainable development in the NEV supply chain through differentiated support policies, dynamic cost management, and technological innovation.

5.2.2 Two-factor sensitivity analysis

In the scenario represented by $E_1(0,0,0)$, NEVSs and NEVMs in the supply chain collude to engage in greenwashing while the GRAs implement lenient regulation. From the perspective of sustainable development, this scenario is highly unfavourable. This reveals the widespread falsification of ESG reports in the NEV industry. Driven by lenient government regulation and market disorder, this practice harms consumer interests, hinders sustainable development goals, and significantly deviates from the national dual carbon targets. The main purpose of this section is to explore how to prevent $E_1(0,0,0)$ from becoming a stable point by adjusting key factors. Table 6 shows the evolution path and stability of the system under different two-factor sensitivity analysis.

Table 6
System evolution path and stability.

Two-factor sensitivity analysis	System strategy evolution	stability
$(B_s\&P_s)\uparrow$	$(0,0,0)\rightarrow(*,0,*)$	instability
$(R_{sc}\&L_s)\uparrow$	Unchanged	ESS
$(R_{mr}\&R_s)\uparrow$	$(0,0,0)\rightarrow(1,*,0)$	instability

Note**:** ↑ *means the value increases,* ∗ *represents evolutionary strategy instability*

(1) The impact of reward and penalty on tripartite game strategies

To explore whether the system can deviate from the stable point $E_1(0,0,0)$ and establish a new stable point when the government strengthens regulatory incentives for a specific link in the supply chain. It also demonstrates the impact of government rewards (B_s) for ESG practices and penalties (P_s) for greenwashing on the strategic choices of three parties under $E_1(0,0,0)$. Let $B_s = P_s = (2,12,22)$. The simulation results are shown in Appendix B. Fig. S1. The results indicate that although increasing regulatory incentives for one part of the supply chain causes the system to deviate from the stable point $E_1(0,0,0)$, it does not establish a new stable point. This suggests that merely strengthening regulatory incentives for one segment of the supply chain may not be sufficient to drive the entire system toward a new stable state. These findings highlight the necessity for the government to comprehensively regulate ESG practices across the entire NEV industry supply chain. For policymakers, this means the need to design more comprehensive regulatory frameworks that consider the interplay between upstream and downstream in the supply chain.

(2) The impact of reputation risk on tripartite game strategies

To explore whether the system deviates from the stable point $E_1(0,0,0)$ to reach a new stable point when one party's greenwashing behaviour leads to an increase in the other party's indirect reputational loss. $R_{sc}L_s$ represents the indirect reputation risk loss caused by a partner's greenwashing behaviour. Let $R_{sc} = (0.3, 0.5, 0.8)$, and $L_s = (2, 7, 12)$. The simulation results are shown in Appendix B. Fig. S2. Despite the indirect impact of the reputation risk coefficient on the partner's revenue, the cooperative relationship within the supply chain remains strong, and both parties may continue to collude in greenwashing. This result underscores the complexity of internal relationships within supply chains. Policymakers should consider designing policy instruments that can effectively disrupt collusion within supply chains, such as strengthening information disclosure requirements or establishing cross-enterprise ESG evaluation systems.

(3) The impact of market response on tripartite game strategies

To explore whether the increase of corporate revenue and market response coefficient will prompt the system to deviate from the initial stable point $E_1(0,0,0)$ and form a new stable point. The simulation results are shown in Appendix B. Fig. S3. Let market response coefficient $R_{mr} = (0.2,0.6,1)$, and the corporate revenue $R_s = (20,60,100)$. The results indicate that as corporate revenue R_s increases, the system tends to deviate from the initial stable point $E_1(0,0,0)$ and move towards a new stable state $(1,0,0)$. This suggests that a strong market reaction to greenwashing significantly encourages NEVSs to adopt ESG practice strategies. It demonstrates that even in the absence of strict government regulation, NEVSs have sufficient motivation to implement ESG measures to avoid reputation loss and sales decline when the market is highly sensitive to greenwashing behaviour. This finding emphasizes the critical role of market mechanisms in driving corporate sustainable development. For companies, it underscores the need to pay closer attention to market responses to ESG practices, positioning ESG strategies as core elements in enhancing brand value and market competitiveness.

5.2.3 Multi-factor sensitivity analysis

$E_1(0,0,0)$ and $E_4(0,0,1)$represent scenarios where NEVSs and NEVMs in the supply chain engage in collusive greenwashing, while GRAs may adopt either lenient or strict regulation. From a sustainability perspective, these strategy set are suboptimal. This section aims to explore the evolutionary paths from the current states $E_1(0,0,0)$ and $E_4(0,0,1)$ towards the ideal state $E_7(1,1,0)$. Table 7 shows the evolution path and stability of the system under different multi-factor sensitivity analysis.

Table 7
System evolution path and stability.

Multi-factor sensitivity analysis	System strategy evolution	stability
$(C_g \& B_s \& B_m)\uparrow$	(0,0,0) → (0,0,0)	ESS
$(C_g \& P_s \& P_m)\uparrow$	(0,0,0) → (0,0,1)	ESS
$(C_{co} \& R_{co})\uparrow$	(0,0,1) → (*,*,*)	instability
$(\Delta C_s \& \Delta C_m \& B_s \& B_m)\uparrow$	(0,0,1) → (1,1,0)	ESS

***Note*：**↑ *means the value increases,* ∗ *represents evolutionary strategy instability*

(1) The impact of different government incentives on the system evolution strategy

This section examines the impact of different government incentives on the system evolution strategy, considering two main scenarios. The first scenario involves government subsidies for corporate ESG practices being greater than the penalties for greenwashing, with parameters set to $C_g = (10,20,30), B_s = B_m = (2,12,22)$. The second scenario involves government penalties for corporate greenwashing being greater than the subsidies for ESG practices, with parameters set to $C_g = (10,20,30), P_s = P_m = (2,12,22)$.

By comparing these two scenarios, the specific effects of different incentives on the evolution of the supply chain can be observed. The simulation results are shown in Appendix B. Fig. S4-S5. When the supply chain colludes in greenwashing, increasing rewards and subsidies for companies implementing ESG practices alone may not effectively mitigate greenwashing behaviour. Instead, it may lead to adverse events such as fraudulent subsidy and arbitrage. Increasing penalties for greenwashing, on the other hand, increases government revenue and potentially shifts the stable point from $E_1(0,0,0)$ to $E_4(0,0,1)$. This indicates that strengthening punitive measures may be more effective than merely increasing rewards in addressing greenwashing issues in the supply chain. For policymakers, this implies the need to design a regulatory system that balances rewards and punishments, with an emphasis on increasing the costs of non-compliance for greenwashing. Business managers should recognize that, in the long term, genuine ESG practices are more beneficial to corporate development than short-term greenwashing.

(2) The evolution path analysis from transition to maturity stage

From the previous analysis, increasing government regulation, particularly penalties for greenwashing, can facilitate the transition from the stable point $E_1(0,0,0)$ to $E_4(0,0,1)$. Next, the conditions required for the transition from $E_1(0,0,0)$ to $E_7(1,1,0)$ are explored. In state $E_4(0,0,1)$, if the government continues to strengthen regulation and penalty, based on the principle that profit is inversely proportional to risk, the increased risk within the supply chain will reduce the cost savings and additional benefits of collusive greenwashing, thereby decreasing its economic attractiveness. By setting $C_{co} = R_{co} = (10,6,2)$, the simulation results are shown in Appendix B. Fig. S6. Although increased government regulation reduces the economic attractiveness of greenwashing, causing a deviation from the stable point, it does not completely transition to a new stable point. This suggests that strengthening regulation alone is not sufficient to achieve a full transition and that the conditions required for the market to transition from an unstable state to a new stable should be further explored.

Combining the previous single-factor and two-factor sensitivity analyses, it is clear that simply controlling one end of the supply chain will not achieve comprehensive ESG practices throughout the supply chain. By readjusting the supply chain parameter configurations, setting $\Delta C_s = \Delta C_m = (70,60,50), B_s = B_m = (1,8,15)$ show that reducing ESG practice costs and increasing rewards can transition the game to the ideal stable point $E_7(1,1,0)$ (Appendix B. Fig. S7). This process demonstrates that low-cost ESG practices combined with government incentives drive companies to continuously improve green innovation technologies, thereby reducing the cost of ESG practice. These findings suggest that policymakers should adopt a multi-pronged approach, including strengthening regulations, providing incentives, and supporting technological innovation. Business managers should actively invest in green innovation technologies, continuously reducing the costs of ESG practices, while seeking government support and industry cooperation to collectively promote sustainable development across the entire supply chain.

In summary, the numerical simulations corroborate and extend the insights gained from the theoretical propositions. The simulations highlight the critical role of reducing ESG implementation costs, providing targeted incentives, and fostering market mechanisms that reward genuine ESG practices. These findings underscore the need for policymakers to design flexible regulatory frameworks that can adapt to the evolving dynamics of the NEV industry. For enterprises in the NEV supply chain, the results emphasize the importance of investing in green innovation technologies and developing long-term ESG strategies that anticipate.

6. Discussion

Our findings reveal that ESG practices in the NEV supply chain exhibit distinct phased characteristics, transitioning from greenwashing in the initial stages to proactive ESG practices in maturity. This novel insight advances our understanding of the dynamic nature of ESG implementation in emerging industries.

During the growth stage, enterprises often lack the motivation for proactive ESG due to the immature understanding and demands of the market concerning ESG. During the transition stage, as market awareness and emphasis on ESG increase, and the government begins to strengthen the formulation and enforcement of related regulations, enterprises start to gradually engage in ESG practices. In this stage, companies begin to attempt ESG measures, but their actions might still be exploratory or reactive changes driven by government and market pressures. This reflects the transitional behaviour of companies adapting to new market demands and government policies, shifting from purely cost considerations to ESG practices.

In the maturity stage, companies recognize the long-term benefits of ESG practices, such as enhanced brand reputation and consumer trust (Asante-Appiah, 2020). ESG practices become an integral part of corporate strategy, and companies proactively engage in ESG practices, thereby promoting sustainable development within the NEV supply chain. Unlike traditional models advocating for continuous strict government regulation(Zhang et al., 2022; Su, 2022; Liu et al., 2023). Our study suggests that the government may adopt a more lenient regulatory strategy as corporate proactivity in ESG compliance increases. This allows the government to reallocate regulatory resources to emerging markets or less mature industries, optimizing overall resource allocation.

Government strategies to combat greenwashing are critical throughout the development of ESG practices. Our research finds that during the development of ESG practices, the government's strategies for combating greenwashing adjust according to different practice stages. Initially, strict punitive measures are essential to shift the supply chain from collusive greenwashing towards genuine ESG practices. As the industry matures, the focus shifts towards subsidies and rewards, encouraging green technological innovations and reducing ESG implementation costs. This phased approach underscores the importance of dynamic government strategies in promoting supply chain sustainability. Current academic research on government strategies for greenwashing governance tends to offer relatively singular incentive policies, either focusing on punitive mechanisms as the main strategy (Sun and Zhang, 2019; Zhang et al., 2022) or emphasizing reward and subsidy (Lu and Yue, 2022; Liu et al., 2023; Zhang et al., 2024). Each approach reveals the effects of different policy measures. However, our study proposes a phased ESG greenwashing governance strategy that better aligns with the development of the NEV industry, providing theoretical and practical guidance for formulating relevant policies to guide companies in ESG practices and strategic planning.

This study examines the dynamic evolutionary mechanisms of ESG practices and greenwashing behaviours in the NEV supply chain. We employed a macroscopic modelling approach, using parameters such as total revenue, total cost, reputation risk coefficient, and partner loss risk to reflect interactions among supply chain members, thus simplifying specific transaction details. To better elucidate these interactions, we incorporated procurement parameters (P and Q) into the model, enhancing its representation of transactional behaviours of supply chain member. The revised model (detailed in Appendix C) maintains our core conclusions while offering new insights into how transaction scale influences ESG practice adoption decisions. Results indicate that supply chain transaction details only affect local revenue distribution without altering the system's equilibrium state, further validating the robustness of our conclusions.

By employing game theory, this study provides a quantitative analytical framework to assess the specific impacts of different policies on supply chain behaviour, complementing existing qualitative analyses and case study-based research (Li et al., 2019; Lee & Raschke, 2023; Zhang et al., 2023; Wang, 2024). Nevertheless, the model’s assumptions in this study are simplified and may not fully capture the complexity of reality. Future research should incorporate social network models to analyze scenarios involving a broader range of stakeholders, enhancing the model's applicability to real-world conditions. Additionally, we acknowledge that the limitation of our current study is the lack of empirical validation, and we suggest that future research focus on testing and refining the model using real-world data from the NEV industry to enhance its practical applicability.

7. Conclusions and Policy Implications

This section summarizes key conclusions and provides policy recommendations based on these findings.

7.1 Major findings

(1) Phased Characteristics of ESG Practices in the Supply Chain

The ESG practices in the NEV supply chain demonstrate distinct phased characteristics. In the early stages, companies often engage in greenwashing to reduce costs due to immature regulatory and market awareness of ESG. During the transitional period, as the market's emphasis on ESG increases and government regulation strengthens, companies transition to proactive ESG measures. In the mature stage, companies have a deeper understanding of ESG, technological advancements reduce the costs of ESG practices, and companies actively adopt and implement these measures.

(2) The dynamic stability of the supply chain depends on the interdependence

The dynamic stability of the supply chain relies not only on the strategy of a single participant but also on the interdependence of all participants' strategies. If only one party of the supply chain receives government incentives while others do not face corresponding incentives or pressures, the overall behavioural pattern remains unchanged. Therefore, to achieve sustainable development, it is necessary for the government to implement comprehensive ESG regulatory strategies across the entire supply chain.

(3) Phased policy adjustments - From greenwashing to supply chain ESG practices

During the growth phase of ESG practices, the government's primary objective is to guide the supply chain towards ESG practices. Simple reward and subsidy mechanisms may be ineffective due to the difficulty of quantifying ESG practices and the risk of abuse. Strict punitive measures significantly promote environmentally friendly behaviors by increasing non-compliance costs. As the transition phase progresses towards maturity, it is recommended that the government focus more on subsidies to encourage companies to adopt and improve green technologies, thereby reducing the cost of ESG practices. As the cost of ESG practices decreases, companies are more likely to adopt these practices proactively.

(4) The significant role of market forces in ESG practices and greenwashing

Market forces exert a significant influence on companies' strategic choices between ESG practices and greenwashing. As market sensitivity to environmental issues increases, NEVMs face pressure to implement substantial ESG measures rather than superficial greenwashing. This emphasizes the important role of market and consumer awareness in influencing sustainable corporate practices, which can be more effective than traditional government regulatory measures. The natural market mechanism, which is based on consumer choice and the natural punishment of dishonest behaviour—effectively forces companies to adopt more responsible ESG actions. Furthermore, the model analysis indicates that as companies become more sensitive to market reactions (increased R_{mr}) and their revenues rise, their perceived risk of greenwashing increases, leading them to avoid greenwashing and turn to genuine ESG practices. This indicates that in instances where market responses are pronounced and company revenues are considerable, companies' behaviour will naturally tend towards more responsible and sustainable practices.

7.2 Policy recommendations

(1) Phased Comprehensive Regulatory Framework

In the growth phase of ESG practice, the government should establish a strict regulatory framework, imposing heavy fines and sanctions on companies prone to greenwashing. This increases the risks and costs associated with greenwashing, thereby discouraging such behaviour. During the transition period, a more flexible policy approach is needed. The government can gradually reduce direct penalties for greenwashing and instead adopt indirect incentives, such as tax breaks or subsidies for companies that successfully implement ESG practices. At maturity, the government should encourage and support companies in reducing ESG practice costs through technological innovation while maintaining a certain level of regulation to ensure the long-term sustainability of the industry. Meanwhile, to ensure the sustainable development of the entire industry, it is imperative that the government implements a comprehensive regulatory framework that encompasses the entire supply chain. This framework must ensure that all links in the chain, from raw NEVSs to end NEVMs, comply with ESG standards.

(2) Public education and market guidance

The government should enhance public education to increase consumer awareness of the importance of ESG, guiding market demand towards green consumption. It is recommended that public campaigns and media should promote environmental awareness related to NEVs and set consumer expectations for corporate ESG practices. This would create societal pressure against greenwashing.

(3) Support for technological R&D and innovation

The government should allocate more resources to support R&D related to ESG, including the use of clean energy, waste recycling, and the development of environmentally friendly materials. Through financial support and tax incentives, companies can be motivated to pursue green technological innovations, reducing the costs associated with ESG practices and enhancing their market competitiveness.

(4) Strategic adaptation for the NEV supply chain members

Drawing on these findings, we propose the following recommendations for NEV Component Suppliers (NEVSs) and NEV Manufacturers (NEVMs): First, our analysis reveals that supply chain stability depends on the interdependence of participants' strategies. NEVSs and NEVMs should align their ESG approaches to mitigate instabilities arising from unilateral actions. Secondly, firms should adapt their ESG strategies according to the industry's developmental stage. During the initial phase of stringent regulation, companies should focus on compliance and foundational ESG practices. As the industry transitions, firms need to proactively implement ESG measures and enhance reputation risk management. Thirdly, supply chain members should continuously monitor market sensitivity to environmental issues. Our model indicates that the market reaction coefficient (R_{mr}) significantly influences firms' strategic choices. Companies should establish effective mechanisms to respond promptly to evolving market expectations regarding ESG practices. Finally, NEVSs and NEVMs should strive to reduce the costs associated with ESG practices. Firms should invest in green technology innovations and actively seek government support to achieve more cost-effective ESG practices. By implementing these recommendations, NEV supply chain members can better manage greenwashing risks, seize market opportunities, and contribute to the industry's sustainable development.

Declaration of competing interest

The authors declare that they have no known competing financial interests’ relationships that could have appeared to influence the work reported in this paper.

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Appendix A.

In response to this valuable feedback, we have added the complete formulas for U_{21}, U_{22}, U_2, U_{31}, U_{31}, and U_3 to the appendix of our manuscript. These formulas provide a comprehensive mathematical representation of the payoff functions for NEVMs and GRAs.

For NEVMs, the payoff functions for adopting "ESG practices" strategy and "greenwashing" strategy are U_{21} and U_{22} respectively, thus obtaining the following equation:

$$U_{21} = (R_m + \Delta R_m - C_m - \Delta C_m + B_m)xz + (R_m + \Delta R_m - C_m - \Delta C_m)x(1-z) + (R_m + \Delta R_m - C_m - \Delta C_m + B_m - R_{sc}L_m)(1-x)z + (R_m + \Delta R_m - C_m - \Delta C_m - \theta R_{sc}L_m)(1-x)(1-z) \quad (1)$$

$$U_{22} = (R_m - C_m - P_m - L_m - C_{ms} - R_{pl} - R_{mr}R_m)xz + (R_m - C_m - L_m - C_{ms} - \theta R_{pl} - \theta R_{mr}R_m)x(1-z) + (R_m - C_m - P_m - L_m - C_{ms} - R_{mr}R_m + C_{co} + R_{co})(1-x)z + (R_m - C_m - L_m - C_{ms} + C_{co} + R_{co} - \theta R_{mr}R_m)(1-x)(1-z) \quad (2)$$

The average expected payoff function for NEVMs is U_2, calculated as: $U_2 = yU_{21} + (1-y)U_{22}$. Similarly, we can obtain the replicator dynamics equation for NEVMs:

$$F(y) = \frac{dy}{dt} = y[U_{21} - U_2] = -y(y-1)\big[C_{ms} - C_{co} - \Delta C_m + \Delta R_m + L_m - R_{co} - \theta L_m R_{sc} + \theta R_{mr}R_m + (C_{co} + R_{co} + +\theta L_m R_{sc} + \theta R_{pl})x + (B_m + P_m + (1-\theta)(R_{mr}R_m - L_m R_{sc}))z + (1-\theta)(R_{pl} + L_m R_{sc})z\big] \quad (3)$$

For GRAs, the payoff functions for adopting "strict regulation" strategy and "lenient regulation" strategy are U_{31} and U_{32} respectively, thus obtaining the following equation:

$$U_{31} = (SE_{esg} - C_g - B_s - B_m)xy + (SE_s - C_g - B_s + P_m)x(1-y) + (SE_m - C_g + P_s - B_m)(1-x)y + (P_s + P_m - C_g - C_E)(1-x)(1-y) \quad (4)$$

$$U_{32} = (SE_{esg} - \theta C_g)xy + (SE_s - \theta C_g)x(1-y) + (SE_m - \theta C_g)(1-x)y + (-\theta C_g - C_E)(1-x)(1-y) \quad (5)$$

The average expected payoff function for GRAs is U_3 calculated as: $U_3 = zU_{31} + (1-z)U_{32}$. Similarly, we can obtain the replicator dynamics equation for g GRAs:

$$F(z) = \frac{dz}{dt} = z[U_{31} - U_3] = z(z-1)\big[(1+\theta)C_g - P_m - P_s + (B_s + P_s)x + (B_m + P_m)y\big] \quad (6)$$

Appendix B.

1. Two-factor sensitivity analysis

(1) The impact of reward and penalty on tripartite game strategies

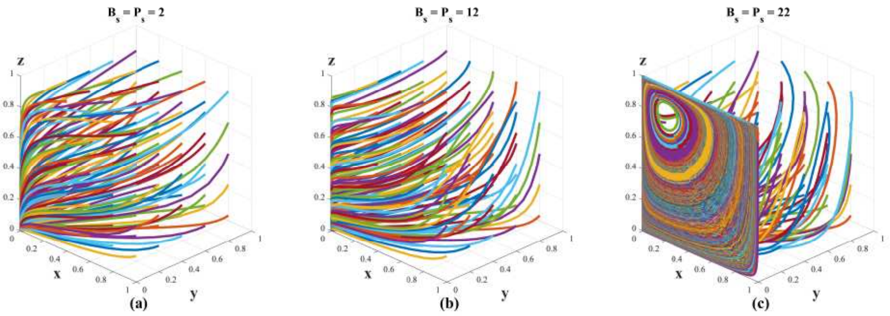

Fig. S1: The impact of $(B_s \& P_s)$ on $E_1(0,0,0)$

(2) The impact of reputation risk on tripartite game strategies

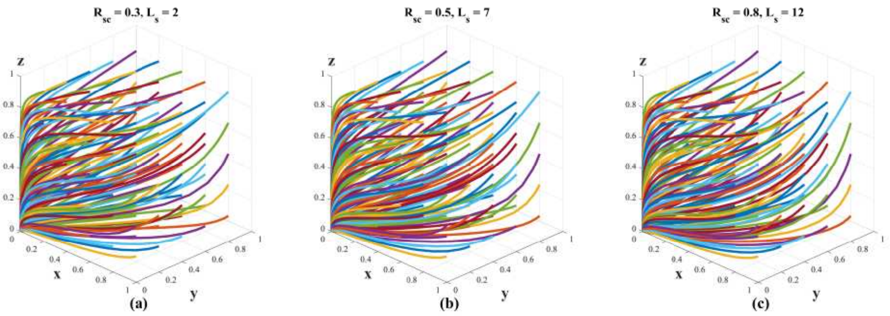

Fig. S2: The impact of $(R_{sc} \& L_s)$ on $E_1(0,0,0)$

(3) The impact of market response on tripartite game strategies

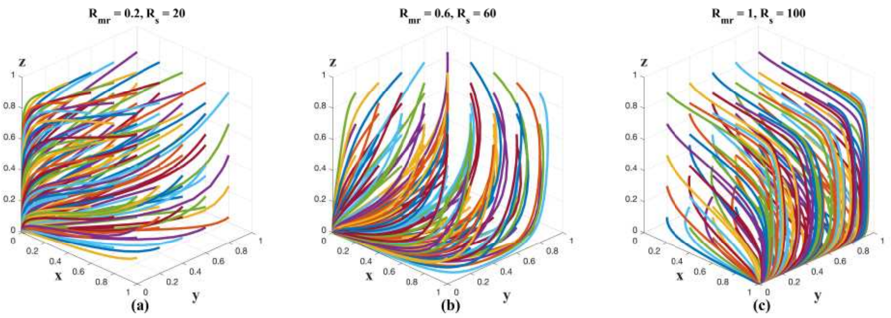

Fig. S3: The impact of $(R_{mr} \& R_s)$ on $E_1(0,0,0)$

2. Multi-factor sensitivity analysis

(1) The impact of different government incentives on the system evolution strategy

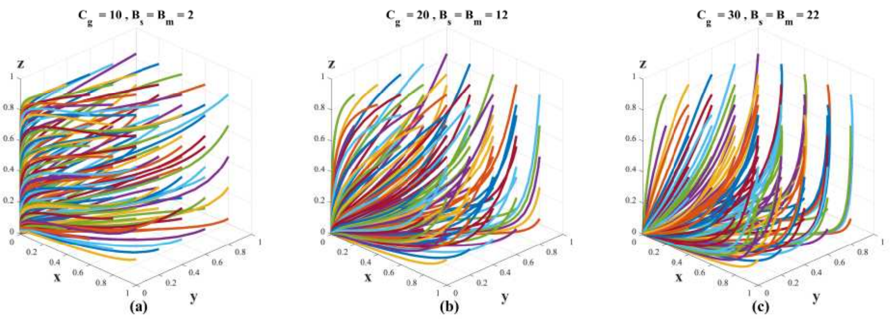

Fig. S4: The impact of $(C_g \& B_s \& B_m)$ on $E_1(0,0,0)$

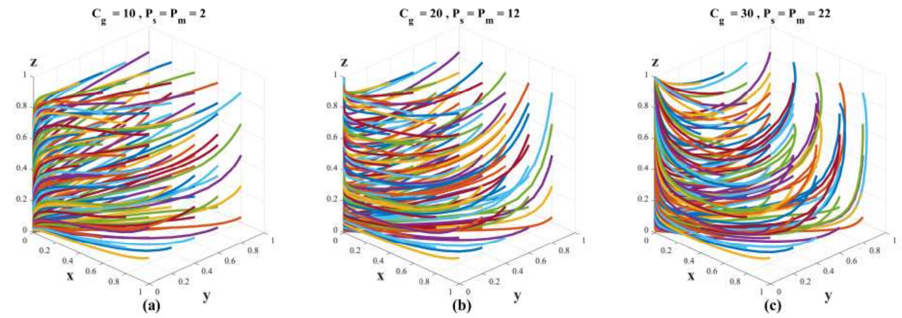

Fig. S5: The impact of $\left(C_g \& P_s \& P_m\right)$ on $E_1(0,0,0)$

(2) The evolution path analysis from transition to maturity stage

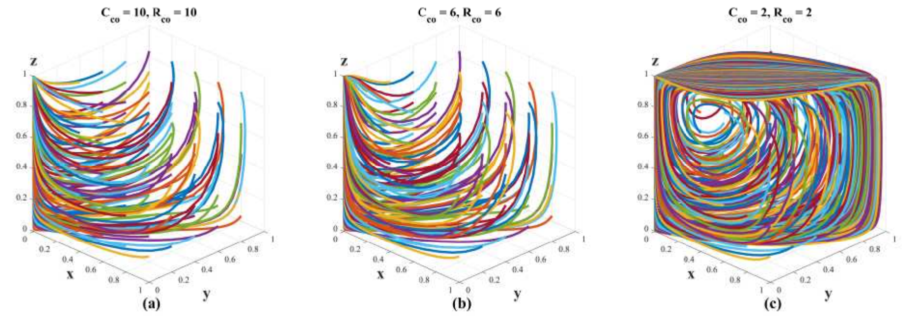

Fig. S6: The impact of $(C_{co} \& R_{co})$ on $E_4(0,0,1)$

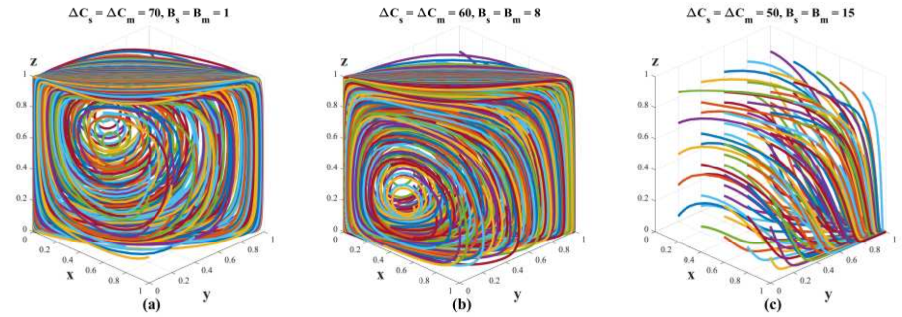

Fig. S7: The impact of $(\Delta C_s \& \Delta C_m \& B_s \& B_m)$ on $E_4(0,0,1)$

Appendix C.

Evolutionary stability analysis of the modified model

1. Incorporation of procurement parameters

We have added procurement parameters (P and Q), where P represents the unit price paid by NEVMs to NEVSs for product procurement, and Q denotes the quantity of products procured by NEVMs from NEVSs. These two parameters directly reflect the transactional behavior between NEVMs and NEVSs. In the original model, R_s represented the total revenue of NEVSs. In the revised model, NEVSs' total revenue is predominantly composed of sales income. PQ represents the total sales revenue NEVSs receive from NEVMs. we posit that $R_s \approx PQ$, predicated on the fundamental assumption that the primary revenue stream for NEVSs is derived from product sales to NEVMs.

The payoff functions when NEVSs and NEVMs choose different strategies ("ESG practices" strategy and "greenwashing") are represented by U_{11}, U_{12} and U_{21}, U_{22}, respectively. The modified payoff functions now explicitly include the procurement payment term ($P * Q$). This adjustment directly reflects the impact of procurement activities on the revenue of supply chain members, allowing the model to better capture supply chain interactions (see the modified Table C-1 for details).

Table C-1

Model parameter descriptions

Game player	Symbol	Parameter description
NEVSs	P	Unit product purchase price paid by NEVMs to NEVSs
	Q	Quantity of products procured by NEVMs from NEVSs.
	C_s, ΔC_s	The basic production cost and extra cost for ESG practices of NEVSs.
	ΔR_s	The extra revenue from ESG practices of NEVSs.
	L_s	Loss of reputation for NEVSs due to greenwashing.
	C_{ss}	Speculative cost for NEVSs.
NEVMs	C_m, ΔC_m	The basic production cost and extra cost for ESG practices of NEVMs.
	R_m, ΔR_m	The baseline revenue and extra revenue from ESG practices of NEVMs.
	L_m	Loss of Reputation due to greenwashing for NEVMs.
	C_{ms}	Speculative cost for NEVMs.
Supply Chain Shared Parameters	C_{co}	Cost savings from collusive greenwashing.
	R_{co}	Extra revenue from collusive greenwashing.
	R_{pl}	The potential loss incurred by the greenwashing party due to the increased likelihood of losing supply chain partners.
	R_{mr}	Market reaction coefficient, measuring sensitivity to greenwashing.
	R_{sc}	Reputation risk coefficient that indicates indirect impact on supply chain reputation ($R_{sc} \in [0,1]$).
GRAs	C_g	The cost of strict supervision by government regulators.
	θ	The cost of coefficient of loose supervision by government regulators ($\theta \in [0,1]$).

B_s, B_m	The rewards of government for NEVSs and NEVMs practising ESG.
P_s, P_m	The penalties imposed by the government on NEVSs and NEVMs practising greenwashing.
SE_s, SE_m	Environmental benefits to the government from the ESG practices of NEVSs and NEVMs, respectively.
C_E	The damage to the environment caused by supply chain greenwashing.
SE_{esg}	Environmental benefits to the government from entire supply chain ESG practices.

Based on the parameter configuration, we can still derive eight strategy combinations for the three-party evolutionary game model involving NEVSs, NEVMs and GRAs. We have recalculated the payoffs under different strategy set and constructed a new payoff matrix (as shown in Table C-2).

Table C-2

The payoff matrix for the tripartite game

NEVSs	NEVMs	GRAs	
		Strict Regulation (z)	Lenient Regulation $(1-z)$
ESG (x)	ESG (y)	$(PQ - C_s) + (\Delta R_s - \Delta C_s) + B_s$ $(R_m - C_m - PQ) + (\Delta R_m - \Delta C_m) + B_m$ $SE_{esg} - (C_g + B_s + B_m)$	$(PQ - C_s) + (\Delta R_s - \Delta C_s)$ $(R_m - C_m - PQ) + (\Delta R_m - \Delta C_m)$ $SE_{esg} - \theta C_g$
	Greenwashing $(1-y)$	$(PQ - C_s - R_{sc}L_s) + (\Delta R_s - \Delta C_s) + B_s$ $(R_m - C_m - PQ - C_{ms}) - (R_{pl} + L_m +$ $R_{mr}R_m) - P_m$ $(SE_s + P_m) - (C_g + B_s)$	$(PQ - C_s - \theta R_{sc}L_s) + (\Delta R_s - \Delta C_s)$ $(R_m - C_m - PQ - C_{ms}) - (\theta R_{pl} + L_m +$ $\theta R_{mr}R_m)$ $SE_s - \theta C_g$
Greenwashing $(1-x)$	ESG (y)	$(PQ - C_s - C_{ss}) - (R_{pl} + L_s + R_{mr}PQ) - P_s$ $(R_m - C_m - PQ - R_{sc}L_m) + (\Delta R_m - \Delta C_m)$ $+ B_m$ $(SE_m + P_s) - (C_g + B_m)$	$(PQ - C_s - C_{ss}) - (\theta R_{pl} + L_s + \theta R_{mr}PQ)$ $(R_m - C_m - PQ - \theta R_{sc}L_m) + (\Delta R_m - \Delta C_m)$ $SE_m - \theta C_g$
	Greenwashing $(1-y)$	$(PQ - C_s) + (R_{co} + C_{co} - C_{ss}) - (L_s +$ $+R_{mr}PQ) - P_s$ $(R_m - C_m - PQ) + (R_{co} + C_{co} - C_{ms}) - (L_m +$ $-R_{mr}R_m) - P_m$ $(P_s + P_m) - (C_g + C_E)$	$(PQ - C_s) + +(R_{co} + C_{co} - C_{ss}) - (L_s +$ $\theta R_{mr}PQ)$ $(R_m - C_m - PQ) + (R_{co} + C_{co} - C_{ms}) -$ $(L_m + \theta R_{mr}R_m)$ $-\theta C_g - C_E$

2. Construction of replicator dynamics equations

Based on the modified model, we have conducted a renewed analysis of system stability and sensitivity. The process begins with calculating the payoff functions and replicator dynamics equations for NEVSs, NEVMs, and GRAs. We then construct a three-dimensional dynamical system equation, determine the system's equilibrium points, and finally derive the Evolutionarily Stable Strategy (ESS) for the tripartite evolutionary game model.

First, for the NEVSs, the payoff functions for adopting the "ESG practice" strategy and the "greenwashing" strategy are denoted as U_{11}, and U_{12}, respectively. The average expected payoff function is represented as U_1, and the replicator dynamics equation is denoted as $F(x)$. These relationships are expressed in the following equations:

$$U_{11} = PQ + \Delta R_s - \Delta C_s - C_s + zB_s - (1-y)[zR_{sc}L_s + (1-z)\theta R_{sc}L_s] \quad (7)$$

$$U_{12} = PQ - C_s - L_s - C_{ss} - P_s z - R_{pl}[yz + \theta y(1-z)] - R_{mr}PQ + (1-y)(C_{co} + R_{co}) \quad (8)$$

$$U_1 = xU_{11} + (1-x)U_{12} \quad (9)$$

$$F(x) = \frac{dx}{dt} = x[U_{11} - U_1] = x(1-x)\big[\Delta R_s - \Delta C_s + L_s + C_{ss} + P_s z + R_{pl}[yz + \theta y(1-z)] + R_{mr}PQ + zB_s - (1-y)[zR_{sc}L_s + (1-z)\theta R_{sc}L_s] - (1-y)(C_{co} + R_{co})\big] \quad (10)$$

Similarly, for the NEVMs, the payoff functions for adopting the "ESG practice" strategy and the "greenwashing" strategy are denoted as U_{21} and U_{22} respectively. The average expected payoff function is represented as U_2, and the replicator dynamics equation is denoted as $F(y)$. These relationships are expressed in the following equations:

$$U_{21} = R_m + \Delta R_m - C_m - \Delta C_m - PQ + zB_m - (1-x)[zR_{sc}L_m + (1-z)\theta R_{sc}L_m] \quad (11)$$

$$U_{22} = R_m - C_m - PQ - L_m - C_{ms} - P_m z - R_{pl}[xz + \theta x(1-z)] - R_{mr}R_m + (1-x)(C_{co} + R_{co})$$

$$U_2 = yU_{21} + (1-y)U_{22} \quad (12)$$

$$F(y) = \frac{dy}{dt} = y[U_{21} - U_2] = y(1-y)\big[\Delta R_m - \Delta C_m + L_m + C_{ms} + P_m z + R_{pl}[xz + \theta x(1-z)] + R_{mr}R_m + zB_m - (1-x)[zR_{sc}L_m + (1-z)\theta R_{sc}L_m] - (1-x)(C_{co} + R_{co})\big] \quad (13)$$

For the GRAs, the payoff functions for adopting the "strict regulation" strategy and the "lenient regulation" strategy are denoted as U_{31} and U_{32} respectively. The average expected payoff function is represented as U_3 and the replicator dynamics equation is denoted as $F(z)$. These relationships are expressed in the following equations:

$$U_{31} = -C_g + xySE_{esg} + x(1-y)SE_s + (1-x)ySE_m - B_s x - B_m y + P_m(1-y) + P_s(1-x) - C_E(1-x)(1-y) \quad (14)$$

$$U_{32} = -\theta C_g + xySE_{esg} + x(1-y)SE_s + (1-x)ySE_m - C_E(1-x)(1-y)$$

$$U_3 = zU_{31} + (1-z)U_{32} \quad (15)$$

$$F(z) = \frac{dz}{dt} = z(1-z)\big[-(1-\theta)C_g - B_s x - B_m y + P_m(1-y) + P_s(1-x)\big] \quad (16)$$

3. System stability analysis

We construct a three-dimensional dynamical system $F(x, y, z)$ by combining the equations $F(x)$, $F(y)$, and $F(z)$:

$$\begin{cases} F(x) = x(1-x)\begin{bmatrix} \Delta R_s - \Delta C_s + L_s + C_{ss} + P_s z + R_{pl}[yz + \theta y(1-z)] + R_{mr}PQ \\ +zB_s - (1-y)[zR_{sc}L_s + (1-z)\theta R_{sc}L_s] - (1-y)(C_{co} + R_{co}) \end{bmatrix} \\ F(y) = y[U_{21} - U_2] = y(1-y)\begin{bmatrix} \Delta R_m - \Delta C_m + L_m + C_{ms} + P_m z + R_{pl}[xz + \theta x(1-z)] + R_{mr}R_m \\ +zB_m - (1-x)[zR_{sc}L_m + (1-z)\theta R_{sc}L_m] - (1-x)(C_{co} + R_{co}) \end{bmatrix} \\ F(x) = z(1-z)\big[(\theta - 1)C_g - B_s x - B_m y + P_m(1-y) + P_s(1-x)\big] \end{cases} \quad (17)$$

Setting $F(x, y, z) = 0$, we obtain 8 pure strategy local equilibrium points. According to Lyapunov's First law, we can confirm that a local equilibrium point is an Evolutionarily Stable Strategy (ESS) only when all eigenvalues of the system's Jacobian matrix are negative. We substitute these 8 equilibrium points into the Jacobian matrix and calculate the eigenvalues for each equilibrium point, as shown in Table C-3.

Table C-3

Jacobian matrix eigenvalues corresponding to each equilibrium point.

Equilibrium Point	λ_1	λ_2	λ_3	stability
(0,0,0)	$P_m - C_g + P_s + \theta C_g$	$C_{ms} - C_{co} - \Delta C_m + \Delta R_m + L_m - R_{co} - \theta L_m R_{sc} + R_m R_{mr}$	$C_{ss} - C_{co} - \Delta C_s + \Delta R_s + L_s - R_{c0} - \theta L_s R_{sc} + PQR_{mr}$	Conditional ESS
(1,0,0)	$P_m - C_g - B_s + \theta C_g$	$C_{ms} - \Delta C_m + \Delta R_m + L_m + \theta R_{pl} + R_m R_{mr}$	$C_{co} - C_{ss} + \Delta C_s - \Delta R_s - L_s + R_{c0} + \theta L_s R_{sc} - PQR_{mr}$	Conditional ESS
(0,1,0)	$P_s - C_g - B_m + \theta C_g$	$C_{ss} - \Delta C_s + \Delta R_s + L_s + \theta R_{pl} + PQR_{mr}$	$C_{co} - C_{ms} + \Delta C_m - \Delta R_m - L_m + R_{c0} + \theta L_m R_{sc} - R_m R_{mr}$	Conditional ESS
(0,0,1)	$C_g - P_m - P_s - \theta C_g$	$B_m - C_{co} + C_{ms} - \Delta C_m + \Delta R_m + L_m + P_m - R_{co} + R_m R_{mr} - L_m R_{sc}$	$B_s - C_{co} + C_{ss} - \Delta C_s + \Delta R_s + L_s + P_s - R_{c0} + PQR_{mr} - L_s R_{sc}$	Conditional ESS
(1,0,1)	$B_s + C_g - P_m - \theta C_g$	$B_m + C_{ms} - \Delta C_m + \Delta R_m + L_m + P_m + R_{pl} + R_m R_{mr}$	$C_{co} - B_s - C_{ss} + \Delta C_s - \Delta R_s - L_s - P_s + R_{c0} - PQR_{mr} + L_s R_{sc}$	Conditional ESS
(0,1,1)	$B_m + C_g - P_s - \theta C_g$	$B_s + C_{ss} - \Delta C_s + \Delta R_s + L_s + P_s + R_{pl} + PQR_{mr}$	$C_{co} - B_m - C_{ms} + \Delta C_m - \Delta R_m - L_m - P_m + R_{c0} - R_m R_{mr} + L_m R_{sc}$	Conditional ESS
(1,1,0)	$\theta C_g - B_s - C_g - B_m$	$\Delta C_m - C_{ms} - \Delta R_m - L_m - \theta R_{pl} - R_m R_{mr}$	$\Delta C_s - C_{ss} - \Delta R_s - L_s - \theta R_{pl} - PQR_{mr}$	Conditional ESS
(1,1,1)	$B_m + B_s + C_g - \theta C_g$	$\Delta C_m - C_{ms} - B_m - \Delta R_m - L_m - P_m - R_{pl} - R_m R_{mr}$	$\Delta C_s - C_{ss} - B_s - \Delta R_s - L_s - P_s - R_{pl} - PQR_{mr}$	instability

Through eigenvalue analysis of the Jacobian matrix, we derived five propositions. The following is a comparative analysis of these propositions obtained from the modified model against the original propositions:

Proposition 1 **(Early market stage):** The modified conditions are: When $C_g - (P_m + P_s) > \theta C_g$, $\Delta R_s - \Delta C_s - \theta L_s R_{sc} < R_{c0} - (C_{ss} - C_{co}) - L_s - PQR_{mr}$, $\Delta R_m - \Delta C_m - \theta L_m R_{sc} < R_{co} - (C_{ms} - C_{co}) - L_m - R_s R_{mr}$, the corresponding evolutionarily stable strategy is {Greenwashing, Greenwashing, Lenient Regulation}, denoted as $E_1(0{,}0{,}0)$. The primary modification is the replacement of $\theta R_s R_{mr}$ with PQR_{mr} in the original model, more accurately reflecting the relationship between market reaction and transaction scale. The condition $(P_m + P_s) > \theta C_g$ remains unchanged, indicating that when the cost of strict ESG regulation is substantially high, the government still opts for a lenient regulatory strategy. In this scenario, when the government's punitive measures for supply chain greenwashing are relatively mild and the cost of ESG practices is considerably high, even though $PQR_{mr} > \theta R_s R_{mr}$, it can still result in $\lambda_2 < 0$, driving collusion in greenwashing within the supply chain. Consequently, the core conclusion of the proposition remains unaltered, demonstrating that under specific conditions, supply chain members and the government still tend to choose greenwashing and lenient regulation, respectively.

Proposition 2 **(Transitional stage):** The modified conditions are: When $C_g + B_s - P_m > \theta C_g$, $\Delta R_s - \Delta C_s - \theta L_s R_{sc} > R_{c0} - (C_{ss} - C_{co}) - L_s - PQR_{mr}$, $\Delta R_m - \Delta C_m < -(C_{ms} + L_m + \theta R_{pl} + R_m R_{mr})$, the evolutionarily stable strategy is {ESG Practices, Greenwashing, Lenient Regulation}, denoted as $E_2(1{,}0{,}0)$. Similarly, when $C_g + B_m - P_s > \theta C_g$, , $\Delta R_m - \Delta C_m - \theta L_m R_{sc} > R_{c0} - (C_{ms} - C_{co}) - L_m - R_m R_{mr}$, $\Delta R_s - \Delta C_s < -\left(C_{ss} + L_s + \theta R_{pl} + PQR_{mr}\right)$, the equilibrium point $E_3(0{,}1{,}0)$ is the ESS, corresponding to the evolutionarily stable strategy {Greenwashing, ESG Practices, Lenient Regulation}. This proposition describes scenarios where, under lenient regulation, one party in the supply chain opts for ESG practices while the other chooses greenwashing.

The primary modifications involve replacing $\theta R_s R_{mr}$ with PQR_{mr}, and $\theta R_m R_{mr}$ with $R_m R_{mr}$. These adjustments more accurately describe the different situations faced by NEVSs and NEVMs in response to market reactions. The conditions$C_g - (P_m + P_s) > \theta C_g$ and $C_g + B_m - P_s < \theta C_g$ remain unchanged, indicating that for the GRAs, adopting a lenient strategy ensures $\lambda_1 < 0$. With $PQR_{mr} > \theta R_s R_{mr}$, $\lambda_2 < 0$ still holds. Given the assumption that $\mathit{\Delta} R_m > \mathit{\Delta} C_m$, the condition $\mathit{\Delta} R_m - \mathit{\Delta} C_m < -(C_{ms} + L_m + \theta R_{pl} + R_m R_{mr})$ holds, ensuring $\lambda_3 < 0$. Consequently, E_2 is the ESS, and by similar reasoning, E_3 is also the ESS. Therefore, the basic structure and conclusions of the proposition remain unchanged after modifying the model.

Proposition 3 **(Transitional stage):** When $(P_m + P_s) - C_g > -\theta C_g$, $\Delta R_m - \Delta C_m + B_m - L_m R_{sc} < R_{c0} - (C_{ms} - C_{co}) - L_m - P_m - R_m R_{mr}, \Delta R_s - \Delta C_s + B_s - L_s R_{sc} < R_{c0} - (C_{ss} - C_{co}) - L_s - P_s - PQR_{mr}$, the corresponding evolutionarily stable strategy is {Greenwashing, Greenwashing, Strict Regulation}, denoted as $E_4(0,0,1)$.

The primary modification lies in replacing $R_s R_{mr}$ with PQR_{mr}, while other conditions remain unchanged. Consequently, $\lambda_1 < 0$ and $\lambda_2 < 0$ from the original proposition can be maintained. The original parameter represented the NEVSs' total revenue, which derives from the NEVMs' procurement within the supply chain. Therefore, it can be assumed that $R_s \approx PQ$. This allows for the preservation of $\lambda_3 < 0$ from the original proposition. According to Lyapunov's first law, E_4 remains an ESS. The revised model more accurately reflects the relationship between the supply chain members' market response and transaction scale. However, the core conclusion of the proposition remains intact, indicating that during the transitional phase, even in the face of strict regulation, supply chain members may still opt for greenwashing behavior.

Proposition 4 **(Transitional stage):** When $(B_s + C_g) - P_m > \theta C_g, \Delta R_s - \Delta C_s - L_s R_{sc} + B_s > R_{c0} - (C_{ss} - C_{co}) - L_s - P_s - PQR_{mr}, \Delta R_m - \Delta C_m < -(B_m + C_{ms} + L_m + P_m + R_{pl} + R_m R_{mr})$, the corresponding evolutionarily stable strategy is {ESG Practices, Greenwashing, Strict Regulation}, denoted as $E_5(1,0,1)$. Similarly, when $\theta C_g > (B_m + C_g) - P_s, \Delta R_s - \Delta C_s < -(B_s + C_{ss} + L_s + P_s + R_{pl} + PQR_{mr}), \Delta R_m - \Delta C_m - L_m R_{sc} + B_m > R_{c0} - (C_{ms} - C_{co}) - L_m - P_m - R_m R_{mr}$, the equilibrium point $E_6(0,1,1)$ is the ESS, corresponding to the evolutionarily stable strategy {Greenwashing, ESG Practices, Strict Regulation}.

The main modification is the replacement of $R_s R_{mr}$ with PQR_{mr} while other conditions remain unchanged. This indicates that $\lambda_1 < 0$ and $\lambda_1 < 0$ from the original proposition are maintained. With $R_s \approx PQ$, $\lambda_2 < 0$ is preserved from the original proposition. Consequently, E_5 and E_6 remain as ESS. Although new parameters have been introduced, the fundamental structure and conclusions of the proposition remain unchanged. This suggests that as the intensity of government regulation increases, supply chain members begin to explore ESG practices.

Proposition 5 **(Market mature stage):** When $\theta C_g < C_g + (B_s + B_m)$, $\Delta R_m > \Delta C_m >$, $\Delta R_s - \Delta C_s > -C_{ss} - L_s - R_{pl} - PQR_{mr}$, the corresponding evolutionarily stable strategy is {ESG Practices, ESG Practices, Lenient Regulation}, i.e., $E_7(1,1,0)$. The core modification is evident in the replacement of $R_s R_{mr}$with PQR_{mr}, while other conditions remain unchanged. This means that $\lambda_1 < 0$ and $\lambda_2 < 0$ are maintained. Based on the original assumption that $\Delta R_s > \Delta C_s$, it follows that $\lambda_3 < 0$ hold, confirming E_7 as the ESS. The revised model more accurately describes the relationship between the supply chain members' market response and transaction scale. However, it does not alter the core conclusion of the original proposition. Both versions describe that in the mature stage of ESG development, the government will adopt a lenient regulatory strategy, and supply chain members will choose to implement ESG practices.

In conclusion, through a systematic stability analysis of the modified model, we can observe that despite the addition of procurement parameters P and Q, the core conclusions and fundamental logical structure of the model remain unchanged. The five propositions continue to correspond to different stages of ESG development in the NEV industry. This demonstrates the robustness of the original model's design in capturing supply chain interactions through simplified transaction details.

4. Sensitivity analysis

Given that the modified model maintains consistency with the original model in its core conclusions, we conducted a simple sensitivity analysis on the newly added parameters P and Q to demonstrate their impact on system evolution.

First, we performed single-factor sensitivity analyses on P and Q separately, studying the effects of different procurement scales on strategy selection by the three parties in the supply chain. Under the conditions of $E_7(1,1,0)$, we set different procurement cost prices P at $(10, 30, 50, 70, 90)$ and different procurement quantities Q at $(1, 3, 5, 7, 9)$. We chose a broad range of parameters to cover various possible scenarios. The simulation results under different P and Q values are presented in Fig. S8-S9. For procurement price P (Fig.S8), as P increases, x (probability of NEVSs choosing ESG practices) and y (probability of NEVMs choosing ESG practices) show a slight decrease, but the magnitude of change is small (not exceeding 5%). z (probability of government choosing strict regulation) remains almost unaffected. For procurement quantity Q (Fig. S9), the impact pattern on x and y is similar to that of P, but with even smaller effects. Similarly, z remains relatively stable.

These results indicate that while an increase in procurement scale slightly reduces the probability of supply chain members choosing ESG practices, the extent of this influence is limited. This may be because as transaction scale expands, enterprises tend to prioritize economic benefits, but the long-term gains from ESG practices remain attractive. Consequently, the addition of new parameters does not alter the overall equilibrium state and evolutionary trend of the system, further validating the robustness of the original model's conclusions.

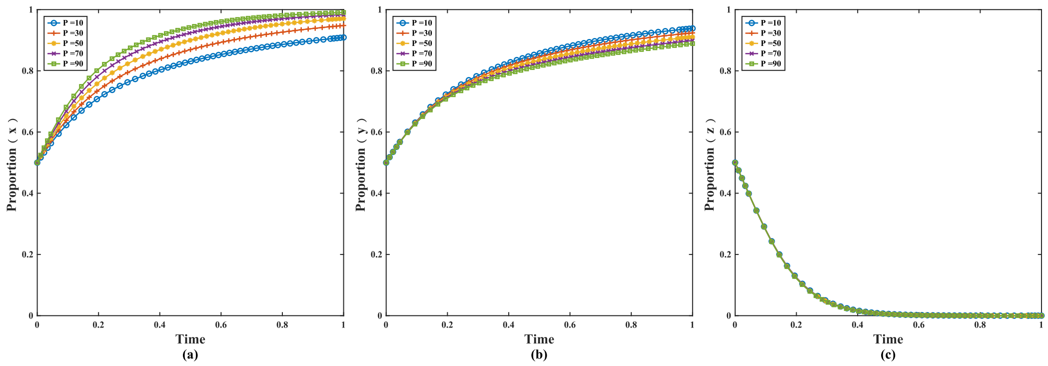

Fig. S8. Evolutionary results under different P

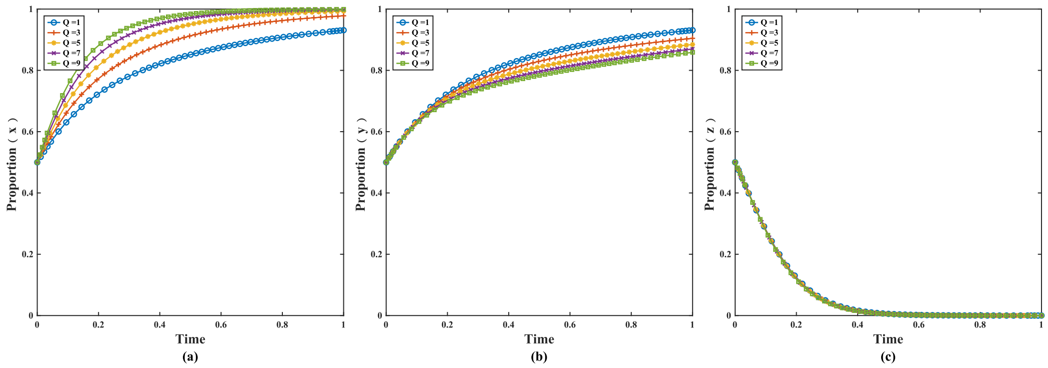

Fig. S9. Evolutionary results under different Q

To gain a deeper understanding of the relationship between market reaction and transaction scale, we conducted a two-factor sensitivity analysis and compared it with the original model. During our stability analysis, we found that the main difference between the propositions in the modified model and the original propositions was the replacement of $\theta R_s R_{mr}$ or $R_s R_{mr}$ with PQR_{mr}, which better reflects the relationship between transaction scale and market reaction. Therefore, while keeping the quantity of products procured by NEVMs from NEVSs constant, we performed a two-factor sensitivity analysis on R_{mr} and P, comparing the results with the two-factor sensitivity analysis of R_s and R_{mr} in the original model. We set the market reaction coefficient $R_{mr} = (0.3,0.5,0.8)$ and the transaction price $P = (20,60,120)$ to explore how these factors influence system evolution under the condition where $E_1(0,0,0)$ is the initial stable point. Fig. S10 presents the new simulation results. The results demonstrate that as the transaction price P and market reaction coefficient R_{mr} increase, the system gradually deviates from $E_1(0,0,0)$, tending towards a new stable state $(1,0,0)$.

Notably, in the modified model, when both P and R_{mr} are at high levels $(P = 120, R_{mr} = 0.8)$, the system transitions more rapidly towards the $(1,0,0)$ state. This indicates that under conditions of large-scale transactions and high market sensitivity, NEVSs have a greater incentive to adopt ESG practices. This trend is similar to the effects of R_s and R_{mr} in the original model (Fig. S3 in Appendix B), indicating that the modified model maintains the evolutionary characteristics of the original conclusions, both emphasizing the crucial role of market mechanisms in driving corporate ESG practices.

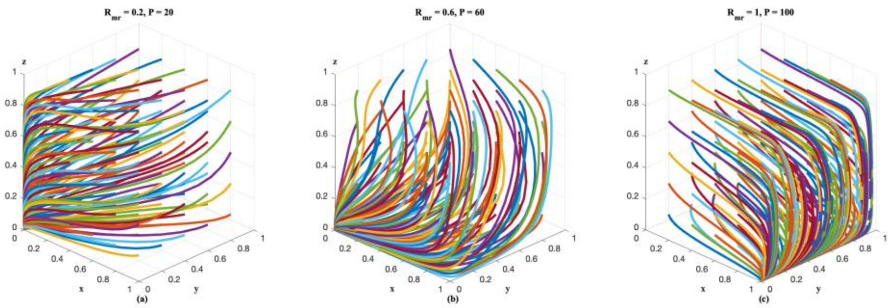

Fig. S10: The impact of $(R_{mr}\&P)$ on $E_1(0,0,0)$

In summary, the newly added procurement parameters (P and Q) primarily affect local revenue distribution without altering the overall equilibrium state and evolutionary trends of the system. The modified model maintains the original dynamic evolutionary characteristics, further confirming the robustness of the conclusions. However, the incorporation of these parameters enhances the model's capacity to describe the actual operations of the supply chain and the interactions among supply chain members, making it more closely aligned with reality and enabling a more comprehensive analysis of the dynamic evolutionary process of ESG practices in the NEV supply chain.