frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 19 December 2023
DOI 10.3389/fenvs.2023.1326322

OPEN ACCESS

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RECEIVED 23 October 2023
ACCEPTED 30 November 2023
PUBLISHED 19 December 2023

CITATION
Huo H and Wang Y (2023), Research on the evolutionary game of multi-agent collaborative supervision of enterprise green behavior driven by big data. *Front. Environ. Sci.* 11:1326322. doi: 10.3389/fenvs.2023.1326322

Research on the evolutionary game of multi-agent collaborative supervision of enterprise green behavior driven by big data

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Based on evolutionary game theory, this paper constructs a tripartite game model—involving the government, enterprises, and environmental protection social organizations—to explore an effective path for the collaborative supervision of corporate green behavior by multiple agents in the context of modern digital technology. The impacts of participating agent strategies are analyzed numerically, and the key factors affecting the ideal state are explored and simulated. The main conclusions and insights are as follows: 1) An increase in government information disclosure can effectively constrain enterprises' behavior, by confronting them with the prospect of loss of reputation. However, if the enterprises' loss of reputation is excessive, they will feel over-regulated, which is not conducive their carrying out green innovation. Information disclosure does, however, have a role to play in transmitting environmental information to the public and environmental protection social organizations in a timely manner to reduce the information gap and promote the formation of multi-dimensional common governance. 2) By using big data, the government can not only save on government costs, but also more accurately identify and monitor in real time enterprises that are causing pollution and that are not using green technology. This can notably promote the evolution of all parties to an ideal state and improve the effectiveness of regulation. 3) When environmental social organizations provide enterprises with the necessary resource supports, this can significantly promote improvements in the enterprises' level of enterprises' green technology innovation. 4) Increased willingness on the part of the public to supervise can enhance the interaction between the public and environmental social organizations, prompting those organizations to actively carry out environmental protection activities and increase their popularity among the public, which will have a positive effect on how the system involving government, enterprises, and environmental protection social organizations evolves.

KEYWORDS

environmental governance, multivariate collaboration, evolutionary game, big data, simulated analysis

1 Introduction

In the green economy era, digital technologies such as big data and "Internet +" are more than crucial. They are not only important to drive the development of a modern environmental governance system but also help organizations collaborate on environmental governance and encourage green innovation in enterprises (Kloppenburg et al., 2022). Even when they are being supervised, enterprises are increasingly seeking to maximize their profit margins by making

inadequate information, or deliberately concealing the bad acts of enterprises in the ecological environment to avoid their own risk costs (Mai et al., 2023). The case of Shanxi Sanwei, which was fined in 2018 for concealing information regarding its involvement in major environmental pollution, showed how enterprises' concealment of environmental violations is becoming increasingly complex, making it difficult to accurately identify enterprises that violate environmental regulations. When enterprises engage in innovation in green technology innovation, it enables them to fulfill their environmental responsibilities effectively. Such green innovation can reduce the occurrence of environmental violations by enterprises and avoid eliminate or reduce pollution and damage to the ecological environment. By effectively monitoring enterprises for supervising the illegal acts, we can further promote green technology innovation by enterprises, reduce operating losses, and transmit green signals to the outside world.

In recent years, many places around the world have issued smart environmental protection cases, and have begun using remote sensing satellites, automatic monitoring, micro-monitoring stations, mobile monitoring equipment and other technologies. Even with this surveillance of compliance with environmental protection regulations, data transparency and strengthening environmental management and monitoring are still urgent issues (Goldstein and Faxon, 2022). Furthermore, Internet participation in environmental management practices has recently gained increasing attention and acceptance among the general public. Public and environmental protection organizations and social organizations increasingly rely on social media, mobile technology, and digital technologies in order to directly observe and obtain a broad range of types of environmental information (Kostka et al., 2020). It is not uncommon for departments to open microblog accounts and adopt other means of communicating official policy decisions to inform the public and environmental protection social organizations about the latest remediation of environmental problems and organize public outreach activities. There are also a number of environmental protection social organizations that have begun to use intelligent map recognition, which has opened up a new stage in AI technology application. Through their efforts to improve the user experience on their platforms, they have gained a high level of public support, as seen in the case of China's "Blue Map App," which enables micro-reporting by users against polluters.

Therefore, this paper analyzes the interactive behavior and equilibrium strategy selection among the game subjects in this situation by constructing a dynamic evolutionary game model involving the local government, enterprises, and environmental protection social organizations. Finally, it analyzes the impacts of the key parameter values on the evolutionary process of each participant using a numerical simulation method. In drawing its conclusions, the study aims to make full use of the technological background of big data and artificial intelligence to provide guidance for the further collaborative promotion of green innovation by enterprises and the development of a low-carbon economy and green society.

2 Related literature

In terms of digital technology and environmental governance, the development of big data can mean that the traditional regulatory mode is superseded with the change from a single governance mode to a multiple collaborative mode. Through the construction of an environmental big data platform, we can obtain environmental data, make the main bodies on the platform interconnected, make the data open and transparent, and improve the immediate response ability of environmental governance (Yu, 2020). The development of the Internet can deal with environmental pollution by promoting technological innovation, industrial upgrading, human capital upskilling, and financial development (Ren et al., 2023). Empirical analysis shows that digitalization can improve environmental governance performance by strengthening the implementation of government environmental regulation, improving public participation, and promoting innovation in green technology by enterprises (Pang et al., 2021). Chen combined practical cases from multiple places to analyze the existing practical problems, and thus proposed an optimization path for technological empowerment and the modernization of environmental governance (Chen, 2023).

In terms of the participants in environmental governance, Bian et al. (2022) explored the regulatory effect of the combination of formal and informal environmental regulation with public participation under heterogeneous government regulations, which can further promote green behavior by enterprises. Yuan (2021) analyzes the influence of the policy burden and the media on decision-making between local governments and manufacturing enterprises, and demonstrated that the supervisory role of the media can inhibit the regulatory capture caused by the policy burden to a certain extent, so as to promote the green technology innovation by enterprises. Chu et al. (2022) established a tripartite evolutionary game model involving the local government, polluting enterprises and the public, and suggested that public supervision could help reduce the regulatory burden on local government and that the public could cooperate with relevant government policies to improve the effectiveness of environmental supervision. Zhou et al. (2022) established an evolutionary game model between the government, the public, polluting enterprises and non-polluting enterprises based on the framework of environmental regulation framework, analyzed the difference in environmental protection contribution and the heterogeneity of innovation drive between the two enterprises, and gave suggestions on how to promote the relationship between collaborative driven green innovation development and environmentally sustainable and coordinated development from the perspective of environmental regulation and collaborative innovation. In addition, some scholars have discussed the relationship between public participation in environmental governance and the monitoring of corporate environmental violations in China (Zhang et al., 2023). By constructing a model involving local governments, third-party testing institutions, and high carbon emission enterprises, Weng et al. (2023) studied the rent-seeking phenomenon that enterprises face in low-carbon environments. Based on the tripartite relationship between local governments, enterprises, and the public, Cao (2021) demonstrated that the public has a certain degree of political influence in supervising environmental governance and can to some extent replace aspects of the government's responsibilities. However, compared with participation by individual members of the public, environmental protection social organizations are more

concentrated; have stronger professional ability; have higher sensitivity and perception of environmental events; have more extensive channels for environmental information collection and greater ability to process such information; and have certain professional and resource advantages (Zhang et al., 2017).

Empowered by digital technology, environmental protection social organizations can take advantage of their professionalism and authority in corporate responsibility disclosure, environmental risk assessment, and compliance, enforcement and work together with the media and the public to achieve a better supervisory effect. In this way, they can improve the efficiency of government supervision and the implementation path of the various subjects participating in the collaborative governance of enterprise greening (Wu and Chen, 2022). Therefore, by relying on digital technologies such as big data and artificial intelligence, environmental protection social organizations can be empowered to detect enterprises' environmental risks by collecting and analyzing relevant information disclosed by enterprises in real time, forming a strong constraint on the exaggeration and falsification of green performance by enterprises, and promoting transparent and open disclosure of information. In this way, environmental protection social organizations can effectively reduce the environmental information asymmetry between the main bodies and protect environmental rights on behalf of the public. It is essential that environmental organizations remain alert to the behavior of enterprises that claim to have gone green and that environmental protection social organizations can use reputation evaluation as a way to reduce the risk of betrayal by enterprises of their environmental commitments (Luo et al., 2020).

As the literature review above suggests, relatively little research has been conducted on how to enhance synergies between the government and environmental protection social organizations in promoting green behavior by enterprises from a digitally driven perspective. By considering the process of interaction between the government, environmental protection social organizations, the public and enterprises, this paper aims to help break out of the situation in which the lack of green technological innovation in enterprises leads to ineffective supervision of illegal acts.

3 Evolutionary game model

3.1 Problem description

This paper studies the strategic choices of the various subjects in green technology innovation, choosing the government, enterprises and environmental protection social organizations as three game subjects, with each subject performing different responsibilities. The model framework is shown in Figure 1.

1) At the government level, the government's role is to guide green innovation, strict supervision can ensure the effective operation of regulatory mechanisms (via incentives for trustworthy environmental protections and punishment of dishonest mechanisms) (Sheng et al., 2020), ensure information openness and transparency, and strengthen the use of scientific and technological means of ensuring compliance with environmental regulations. The government can severely crack down on environmental violations and guide the enterprises' environmental self-discipline.
2) At the enterprise level, faced with the high costs of green innovation (Li and Gao, 2022) in terms of factors such as obtaining social capital, improving competitiveness, and reducing risks and production costs, enterprises may seek to obtain short-term advantages through "green bleaching" Environmental compliance means that enterprises comply with the relevant laws, regulations and rules; disclose true, effective, and accurate information regarding their enterprises, in a timely manner; make their operations more transparent; and reduce environmental pollution by updating green environmental protection equipment and increasing their investments in research and development on innovative green technology Enterprises compete against each other to win green subsidies from the government and green financing from financial institutions by showing positive green performance, fulfilling their corporate responsibilities, and achieving sustainable development. Enterprises are generally paying more attention to improving environmental integrity awareness and credit level.
3) At the level of environmental social organizations, active involvement means that they constantly improving their scale and strength, providing sustainable cooperation and introducing resources to enterprises with good environmental performance (Cui et al., 2022). Though holding exchange meetings, introducing green suppliers, and promoting cooperation and signing contracts to promote environmental cooperation between enterprises. In addition, they use independent platforms or apps to transmit environmental information, guide the public to interact on the platform, organizing boycotts against undisciplined enterprises through publicity campaigns, and obtain real-time environmental information disclosed by the government. They use big data and other advanced technologies to strictly supervise enterprises and evaluate their relevant data, track their follow-up rectification behavior, and provide timely feedback to the government.

3.2 Model assumptions

3.2.1 Assumption 1

The participants in the game are subject to all bounded rationality, and all three parties have two strategic choices. The government strategy set is: [big data regulation, traditional regulation]; the enterprise's strategy set is: [environmental compliance, environmental violation]; and the environmental protection social organization strategy set is: [active intervention, general intervention].

3.2.2 Assumption 2

Government. In the process of multiagent supervision of enterprises' green behavior, the government can use big data platforms to carry out environmental monitoring and conduct big data analysis and use other methods to detect abnormalities in enterprises' environmental behavior in a timely manner, thus

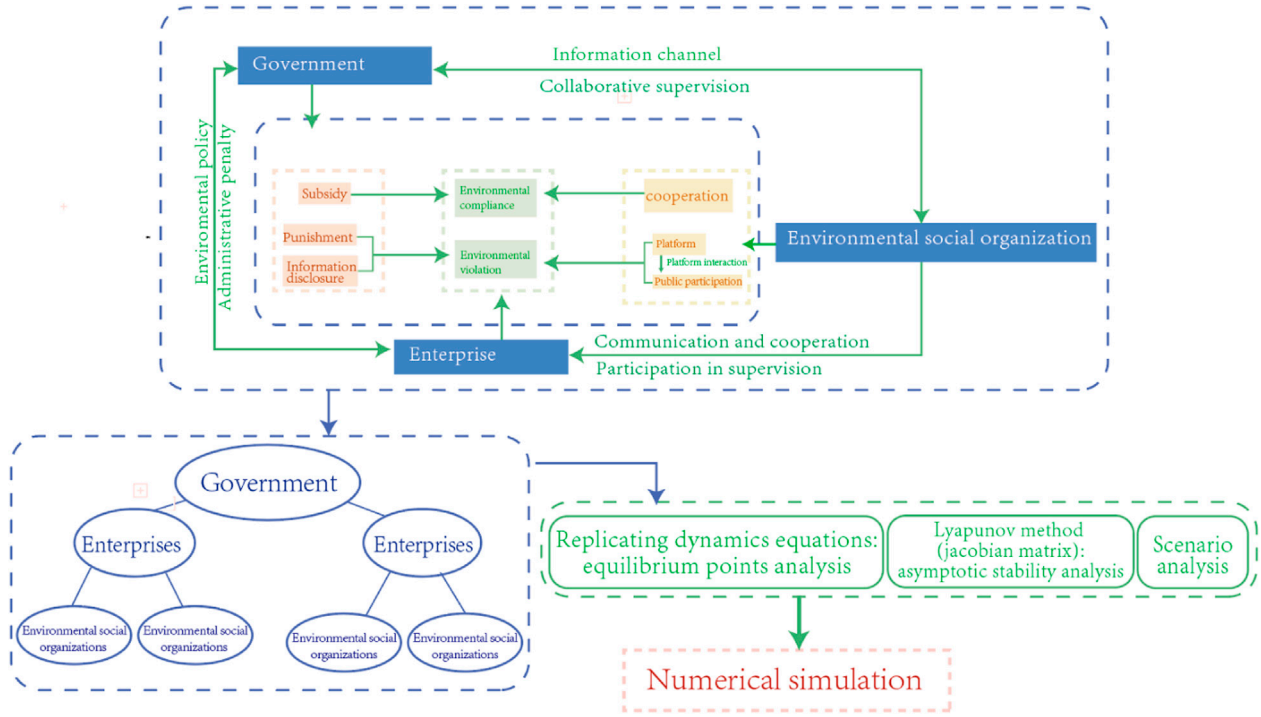

FIGURE 1
Model framework.

achieving a strong supervisory effect. Therefore, the cost of strong government supervision under the big data regulatory scenario is C_1, the benefit is R_1, and the probability of the existence of environmental risks in enterprises monitored by big data regulation is m, $m \in [0, 1]$. The traditional regulation scenario means that the government relies more on investing in manpower to regulate, but the supervisory effect in terms of the ability to detect violations by enterprises under traditional regulation is not satisfactory. At this time, the cost of weak government regulation is C_2, the benefit is R_2, and the probability of traditional regulation successfully monitoring enterprises for environmental risks is n, $n \in [0, 1]$. Government departments publicize the results of environmental supervision and administrative penalties, and publicity by environmental protection social organizations with excellent performance is k, $k \in [0, 1]$ (big data regulation $k = 1$). The active involvement of environmental social organizations in traditional government regulation will help the government save on the costs of supervision.

3.2.3 Assumption 3

Enterprises. Environmental compliance means that the enterprise can regulate its own environmental behavior; constantly improve and update its environmental protection facilities and technologies; and carry out green technological innovation. At this time, the cost of environmental compliance is C_3 and the benefit is R_3. An environmental violation means that the enterprise has failed to practice green behaviors in accordance with the relevant regulations and that the enterprise's environmental risk is high, in which case the cost of environmental violation is C_4 and the benefit is R_4. When the enterprise's environmental performance is poor, it will suffer from a negative image due to the government's information disclosure and suffer a certain loss of reputation, S. In addition, when environmental protection social organizations actively intervene, they can promote the environmental protection mission to enterprises, establish channels of communication and interaction with enterprises on environmental protection issues, provide necessary resource supports, and jointly promote green development, which increases the benefits to enterprises, H.

3.2.4 Assumption 4

Environmental protection social organizations have become the main channel for the public to obtain information by establishing corresponding digital platforms or applications to centrally publish relevant information about the environmental activities of enterprises. The cost of active intervention is C_5 and the benefit is R_5. General intervention refers to the operation of the organization at a lower cost, mainly to carry out environmental protection publicity and education; the cost of general intervention is C_6 and the benefit is R_6. After the information is disclosed by the government, environmental social organizations can obtain relevant information about enterprises in a timely manner, enabling them to continuously follow up on the enterprises' rectification activities; the value of the information obtained is X. When environmental social organizations actively intervene, they seek financial support from foundations and other channels due to the high costs involved in this type of activity; the value of the information obtained is Q. The benefits obtained from the public being active online on the environmental social organization's platform and environmental interaction within the platform (participation in publishing environmental activities, environmental education and publicity,

TABLE 1 Model parameter settings.

Symbols	Definition
C_1, R_1	Costs and benefits of strong government regulation under the big data regulation strategy
C_2, R_2	Costs and benefits of weak government regulation under the traditional regulation strategy (C_2>C_1)
m,n	Probability of successful monitoring of enterprises' environmental risks by big data supervision and traditional regulation ($m > n$)
B, P	Government subsidies and penalties for enterprises that comply with environmental regulations and those that commit environmental violations by enterprises
C_3, R_3	Costs and benefits of environmental compliance by enterprises(C_3>C_4)
C_4, R_4	Costs and benefits of environmental violations by enterprises
k	Government departments publicizing the results of environmental regulation and administrative punishments and the publicity generated by environmental protection social organizations with excellent performance, k∈(0,1) (big data regulation $k = 1$)
S	Loss of reputation caused by government information disclosure
C	In traditional government regulation, the active involvement of environmental protection social organizations will help save on the costs of government regulation
C_5, R_5	Costs and benefits of active intervention
C_6, R_6	Costs and benefits of general intervention (only low-cost activities such as environmental publicity and education) (C_5>C_6)
H	Benefits of environmental protection cooperation (provision of green information and resources) provided by environmental protection social organizations to enterprises that are in compliance with environmental regulations
L	The public is active online, and the benefits from environmental interaction (participation in the release of environmental protection activities, environmental education publicity, etc.) within the platform
X	Value of information obtained by environmental protection social organizations after government information disclosure
p	Probability of public participation in environmental supervision of enterprises
Q	Environmental protection social organizations actively seek financial support from foundations and other channels

TABLE 2 Payoff matrix.

Government	Enterprises	Environmental protection social organizations	
		Active intervention	General intervention
Big data regulation	Environmental compliance	R_1-C_1-B	R_1-C_1-B
		$B + H + R_3-C_3$	$B + R_3-C_3$
		$Q + pL + R_5-C_5$	R_6-C_6
	Environmental violation	$pU + nP + R_1-C_1$	$pU + nP + R_1-C_1$
		$S + N + R_4-C_4-mP$	$S + R_4-C_4-mP$
		$Q + X + pL + R_5-C_5$	R_6-C_6
Traditional regulation	Environmental compliance	$C + R_2-C_2-B$	$B + R_3-C_3$
		$B + H + R_3-C_3$	$B + R_3-C_3$
		$Q + pL + R_5-C_5$	R_6-C_6
	Environmental violation	$pU + C + nP + R_2-C_2$	$pU + nP + R_2-C_2$
		$kS + N + R_4-C_4-nP$	$kS + R_4-C_4-nP$
		$Q + kX + pL + R_5-C_5$	R_6-C_6

etc.) is L. The probability of public participation in monitoring is assumed to be p, p ∈[0, 1].

The parameter settings in the model are shown in Table 1.

According to the aforementioned assumptions, the payment matrix can be obtained as shown in Table 2 below:

3.3 Model analysis

According to the payment matrix, the expected net income of the government choosing the "big data regulation" strategy, "traditional regulation" strategy, and the average expected net income are as follows.

$$U_{11} = yz(R_1\text{-}C_1\text{-}B)+y(1\text{-}z)(R_1\text{-}C_1\text{-}B) + (1\text{-}y)z(pU + mP + R_1\text{-}C_1) + (1\text{-}y)(1\text{-}z)(pU + mP + R_1\text{-}C_1) \quad (1)$$

Expected benefits of government traditional regulation:

$$U_{12} = yz(C + R_2\text{-}C_2\text{-}B) + y(1\text{-}z)(R_2\text{-}C_2\text{-}B) + (1\text{-}y)z(pU + nP + C + R_2\text{-}C_2) + (1\text{-}y)(1\text{-}z)(pU + mP + R_2\text{-}C_2) \quad (2)$$

Average expected earnings of government:

$$\overline{U_1} = xU_{11} + (1\text{-}x)U_{12} \quad (3)$$

The replication dynamic equation of government is as follows:

$$F(x) = dx/dt = x(1\text{-}x)(C_2\text{-}C_1 + R_1\text{-}R_2\text{-}zC + (m\text{-}n)P\text{-}ymP + ynP) \quad (4)$$

Expected benefits of enterprise environmental compliance:

$$U_{21} = xz(B + H + R_3\text{-}C_3) + x(1\text{-}z)(B + R_3\text{-}C_3) + (1\text{-}x)z(B + H + R_3\text{-}C_3) + (1\text{-}x)(1\text{-}z)(B + R_3\text{-}C_3) \quad (5)$$

Expected benefits of enterprise environmental violations:

$$U_{22} = xz(S + N + R_4\text{-}C_4\text{-}mP) + x(1\text{-}z)(S + R_4\text{-}C_4\text{-}mP) + (1\text{-}x)z(kS + N + R_4\text{-}C_4\text{-}nP) + (1\text{-}x)(1\text{-}z)(kS + R_4\text{-}C_4\text{-}nP) \quad (6)$$

Average expected earnings of enterprises:

$$\overline{U_2} = yU_{21} + (1\text{-}y)U_{22} \quad (7)$$

The replication dynamics equations of the enterprises are as follows:

$$F(y) = dy/dt = y(1\text{-}y)[B\text{-}C_3 + C_4 + R_3\text{-}R_4 + nP\text{-}kS + zH\text{-}zN\text{-}xS + xmP\text{-}xnP + xkS] \quad (8)$$

Expected benefits of active intervention of environmental protection social organizations:

$$U_{31} = xy(Q + pL + R_5\text{-}C_5) + x(1\text{-}y)(Q + X + pL + R_5\text{-}C_5) + (1\text{-}x)y(Q + pL + R_5\text{-}C_5) + (1\text{-}x)(1\text{-}y)(Q + X + pL + R_5\text{-}C_5) \quad (9)$$

Expected benefits of general intervention of environmental protection social organizations:

$$U_{32} = xy(R_6\text{-}C_6) + R_6\text{-}C_6x(1\text{-}y)(R_6\text{-}C_6) + (1\text{-}x)R_6\text{-}C_6) + (1\text{-}x)y(R_6\text{-}C_6) + (1\text{-}x)(1\text{-}y)(R_6\text{-}C_6) \quad (10)$$

Average expected return of environmental protection social organizations:

$$\overline{U_3} = zU_{31} + (1\text{-}z)U_{32} \quad (11)$$

The replication dynamics equations of environmental protection social organizations are as follows:

$$F(z) = dz/dt = z(1\text{-}z)[C_6\text{-}C_5 + Q + R_5\text{-}R_6 + pL + x(1\text{-}y)X + (1\text{-}x\text{-}y)kX + xkX] \quad (12)$$

3.4 Stability analysis of strategies of different agents over the course of evolution

3.4.1 Analysis of the stability of government strategy

Situation 1: If $z = z_0 = (ymP - ynP - (m-n)P + C_1 - C_2 - R_1 + R_2)/C$, then $F(x) \equiv 0$, so x takes any value as a stable state of evolution. At the same time, this also shows that the government has stable strategies regardless of their choice of strategies, that will not change over time. If $z > z_0$, then $F'(1) > 0$ and $F'(0) < 0$. Therefore, the government will choose the "traditional regulation" strategy as an evolutionarily stable strategy. If $z < z_0$, then $F'(1) < 0$ and $F'(0) > 0$. Therefore, the government will choose the "big data regulation" strategy as the evolutionarily stable strategy.

3.4.2 Analysis on the stability of Enterprises strategies.

Situation 1: If $x = x_0 = (B\text{-}C_3+C_4+R_3\text{-}R_4+nP\text{-}kS + z(H\text{-}N)/((n\text{-}m)P+(1\text{-}k)S)$, then $F(y) \equiv 0$, so, any strategy is stable. If $x > x_0$, then $F'(0) > 0$and $F'(1) < 0$. So, so enterprises will choose the strategy of "environmental compliance". If $x < x_0$, then $F'(1) < 0$and $F'(0) > 0$. So, so enterprises will choose the strategy of"environmental violation."

3.4.3 Analysis on the stability of environmental protection social organizations strategies

Situation 1: If $y = y_0 = (C_6\text{-}C_5+Q + R_5\text{-}R_6+Lp + kX + xX\text{-}xkX)/(Xk + Xx\text{-}Xkx)$, then $F(z) \equiv 0$, so z takes any value as an evolution stable state in this situation. At the same time, it also shows that the environmental protection social organizations have stable strategies regardless of their choice of strategies and will not change with time. If $y > y_0$, then $F'(0)>0$and $F'(1)<0$. So, active intervention is the stability strategy of environmental protection social organizations. If $y < y_0$, then $F'(0) < 0$and $F'(1) > 0$. So, general intervention is the stability strategy of environmental protection social organizations.

3.5 Analysis of stability strategies of tripartite evolutionary game

The equilibrium point of the system can be obtained from: $F(x) = 0$, $F(y) = 0$, $F(z) = 0$. According to the replication dynamic equations, eight pure strategy equilibrium points and eigenvalues of the system can be obtained, as shown in Table 3.

In case 1, the evolutionary stability point is (0,0,1), this article is based on the assumption: $C + C_1 - C_2 - R_1 + R_2 - mP + nP > 0$, $B - C_3 + C_4 + H - N + R_3 - R_4 - kS + nP < 0$, $C_5 - C_6 - Q - R_5 + R_6 + X - pL < 0$. The active involvement of environmental protection social organizations in saving government supervision costs is greater than the government's fine income for violating enterprises. The benefits of active involvement of environmental protection social organizations are greater than the benefits of general intervention, and the benefits of enterprise environmental compliance are less than the benefits of environmental violations. At this time, the government chooses traditional supervision, while enterprises choose environmental violations. Only environmental protection social organizations actively intervene, and the overall environmental behavior supervision of enterprises is not significant.

In case 2, the evolutionary stability point is (1,0,0), this article is based on the assumption: $C_1 - C_2 - R_1 + R_2 - mP + nP < 0$, $B - C_3 + C_4 + R_3 - R_4 - S + mP < 0$, $C_5 - C_6 - Q - R_5 + R_6 - X - pL > 0$. The effectiveness of big data regulation is higher than that of traditional regulation, and the benefits of corporate environmental compliance

TABLE 3 Eigenvalues of the game equilibrium solution.

Equilibrium point	Eigenvalue			
	λ_1		λ_2	λ_3
E_1 (0,0,0)	$-(C_1 - C_2 - R_1 + R_2 - mP + nP)$	$B - C_3 + C_4 + R_3 - R_4 - kS + nP$	$-(C_5 - C_6 - Q - R_5 + R_6 + kX - pL)$	Instability point
E_2 (0,1,0)	$-(C_1 - C_2 - R_1 + R_2)$	$C_3 - B - C_4 - R_3 + R_4 + kS - nP$	$-(C_5 - C_6 - Q - R_5 + R_6 - pL)$	Instability point
E_3 (0,0,1)	$-(C + C_1 - C_2 - R_1 + R_2 - mP + nP)$	$B - C_3 + C_4 + H - N + R_3 - R_4 - kS + nP$	$C_5 - C_6 - Q - R_5 + R_6 + X - pL$	Condition①
E_4 (0,1,1)	$-(C + C_1 - C_2 - R_1 + R_2)$	$C_3 - B - C_4 - H + N - R_3 + R_4 + kS - nP$	$C_5 - C_6 - Q - R_5 + R_6 - pL$	Instability point
E_5 (1,0,0)	$C_1 - C_2 - R_1 + R_2 - mP + nP$	$B - C_3 + C_4 + R_3 - R_4 - S + mP$	$-(C_5 - C_6 - Q - R_5 + R_6 - X - pL)$	Condition②
E_6 (1,1,0)	$C_1 - C_2 - R_1 + R_2$	$C_3 - B - C_4 - R_3 + R_4 + S - mP$	$-(C_5 - C_6 - Q - R_5 + R_6 - pL)$	Condition③
E_7 (1,0,1)	$C + C_1 - C_2 - R_1 + R_2 - mP + nP$	$B - C_3 + C_4 + H - N + R_3 - R_4 - S + mP$	$C_5 - C_6 - Q - R_5 + R_6 + X - pL$	Condition④
E_8 (1,1,1)	$C + C_1 - C_2 - R_1 + R_2$	$C_3 - B - C_4 - H + N - R_3 + R_4 + S - mP$	$C_5 - C_6 - Q - R_5 + R_6 - pL$	Condition⑤

are less than those of environmental violations. The benefits of active intervention by environmental protection social organizations are less than those of general intervention. At this time, the government chooses big data regulation, and enterprises will violate environmental regulations. Environmental protection social organizations choose general intervention to save costs.

In case 3, the evolutionary stability point is (1,1,0), this article is based on the assumption: $C_1 - C_2 - R_1 + R_2 < 0$, $C_3 - B - C_4 - R_3 + R_4 + S - mP < 0$, $C_5 - C_6 - Q - R_5 + R_6 - pL > 0$. The benefits of big data regulation are higher than those of traditional regulation, the benefits of corporate environmental compliance are greater than those of environmental violations, and the benefits of active intervention by environmental protection social organizations are less than those of general intervention. At this time, the government chooses big data regulation, enterprises will comply with environmental regulations, and environmental protection social organizations will choose general intervention.

In case 4, the evolutionary stability point is (1,0,1), this article is based on the assumption: $C + C_1 - C_2 - R_1 + R_2 - mP + nP < 0$, $B - C_3 + C_4 + H - N + R_3 - R_4 - S + mP < 0$, $C_5 - C_6 - Q - R_5 + R_6 + X - pL < 0$. This indicates that the effectiveness of big data regulation is higher than that of traditional regulation, and the benefits of corporate environmental compliance are less than those of environmental violations. The benefits of active intervention by environmental protection social organizations are greater than those of general intervention. At this time, if the government chooses big data regulation, enterprises will violate environmental regulations, and environmental protection social organizations will actively intervene.

In case 5, the evolutionary stability point is (1, 1,1), this article is based on the assumption: $C + C_1 - C_2 - R_1 + R_2 < 0$, $C_3 - B - C_4 - H + N - R_3 + R_4 + S - mP < 0$, $C_5 - C_6 - Q - R_5 + R_6 - pL < 0$. The effectiveness of big data regulation is higher than that of traditional regulation, and the benefits of corporate environmental compliance are greater than those of environmental violations. The benefits of active intervention by environmental protection social organizations are greater than those of general intervention. At this time, the government chooses big data regulation, and enterprises will comply with environmental regulations. Environmental protection social organizations choose to actively intervene in order to save costs. All three parties choose active strategies, collaborative governance is effectively utilized, and the game system is in its optimal state.

4 Evolutionary game model

In order to intuitively reflect on evolutionary trends of the system, this study uses numerical simulation to examine the influence of governmental tools, environmental social organizations, and the public on enterprises' green decision-making. The parameter variables related to the enterprises are taken as the key parameters to explore the impact of changes in them on the evolutionary equilibrium results.

Set the parameter values as follows: $C = 1$, $n = 0.5$, $C_1 = 3$, $C_2 = 6$, $R_1 = 5$, $R_2 = 3$, $H = 3$, $C_3 = 6$, $L = 2$, $X = 2$, $Q = 2$, $p = 0.6$, $N = 2$, $m = 0.8$, $P = 4$, $k = 0.6$, $n = 0.5$, and $S = 2$. The initial values for each subject are 0.5, 0.5, and 0.5.

4.1 The impact of different initial intentions on evolutionary results

The pure strategy equilibrium E8 (1,1,1) indicates that big data regulation by the government, environmental compliance by enterprises, and the active involvement of environmental protection social organizations are the best ideal states for all entities to jointly promote the development of green innovation in enterprises. Therefore, the government needs to actively apply big data supervision and make reasonable use of regulatory means to promote environmental protection cooperation and co-construction by enterprises and environmental protection social organizations.

Therefore, on the basis of meeting the E8 (1,1,1) parameter conditions, to more clearly verify the impact of different initial states, different initial values for the three parties are used to

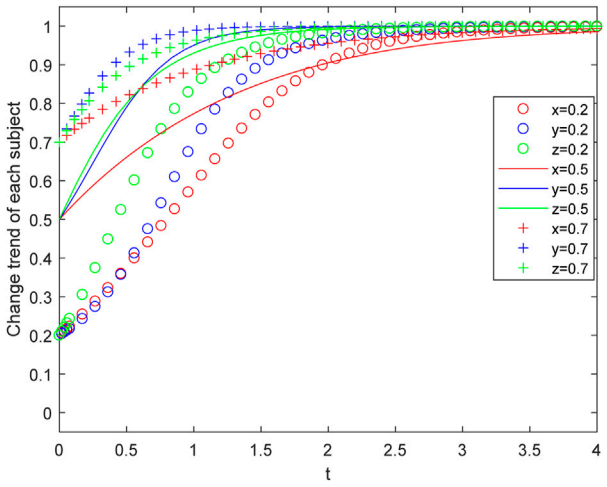

FIGURE 2
Results of simultaneous increases in the initial proportions.

simulate the evolutionary process toward a stable state of the system. We set the initial values of x, y, and z to (0.2, 0.2, 0.2), (0.5, 0.5, 0.5), and (0.7, 0.7, 0.7), respectively. The simulation results are shown in Figure 2. Increasing the initial values of x, y, and z can significantly improve the rate of convergence and accelerate the rate of convergence of each subject to 1. In other words, it can speed up the government's adoption of the "big data regulation" strategy, enterprises' adoption of the "environmental compliance" strategy, and environmental protection social organizations' adoption of the "active involvement" strategy.

4.2 The impact of key parameters on game system

1) Keep other parameters unchanged and change the value of government information disclosure K, as shown in Figure 3. With the increase in government information disclosure, the speed at which the government approaches 1 will slow down due to increased regulatory costs. However, information disclosure leads toa tendency on the part of enterprises to become environmentally compliant, accelerating the speed at which they tend to become good, and will also lead to an increase of the value of the information obtained by environmental protection social organizations from the information, ultimately leading to the tendency of environmental protection social organizations to become more inclined toward 1.
2) If we keep other parameters unchanged while changing the value of government regulatory effectiveness (m and P), as shown in Figure 4, as government regulatory effectiveness is enhanced, the stability of the government and enterprises in maintaining positive strategies can be significantly increased, with little impact on environmental protection social organizations. Because the government uses big data analysis, it can obtain enterprise environmental data from enterprises in real time, accurately identify violations by enterprises; greatly improve the probability of successful supervision; save on manpower, transportation, and other regulatory costs; and significantly improve the regulatory effectiveness. Due to the high pressure of law enforcement, enterprises cannot drill regulatory loopholes in order to avoid the consequences of violations, making them more likely to choose to carry out cleaner production

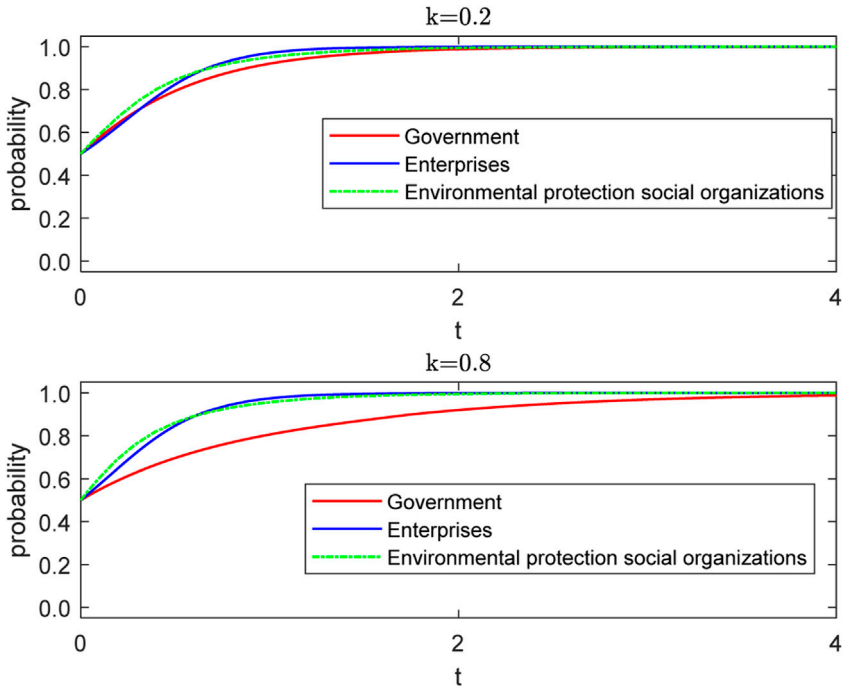

FIGURE 3
The influence of k on the game system.

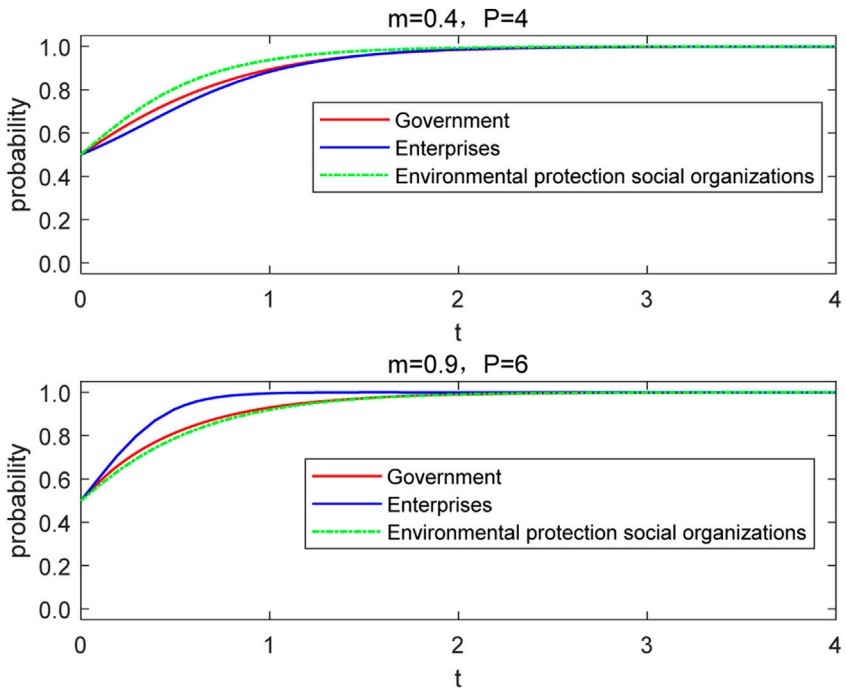

FIGURE 4
The influence of *m* and *P* on the game system.

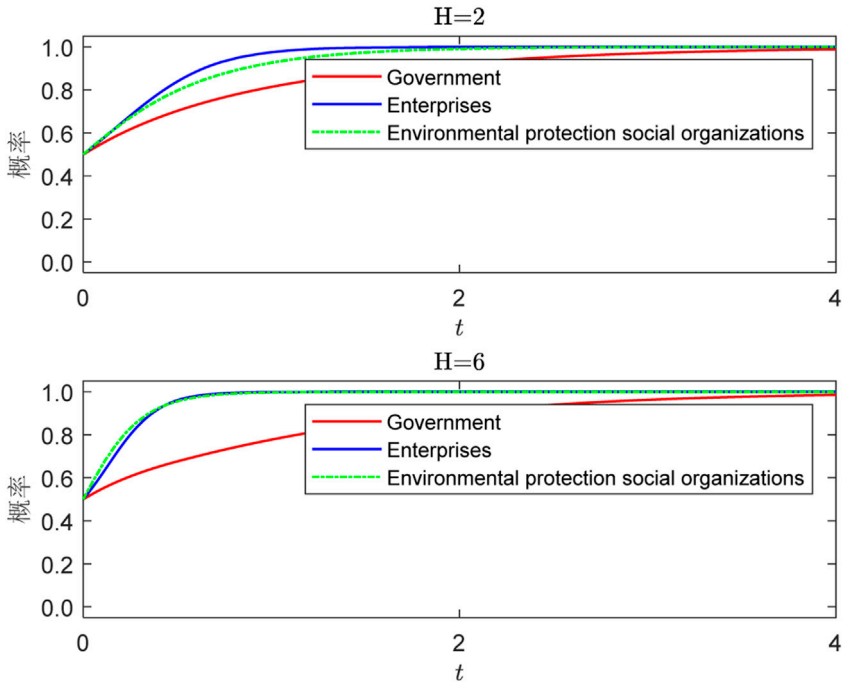

FIGURE 5
The influence of *H* on the game system.

independently, and actively explore green production technologies in order to obtain government subsidies, and minimize the negative external impacts of production.

3) We keep other parameters unchanged and change the probability value of public participation in supervision, as shown in Figure 5. It can be seen that the environmental protection cooperation provided

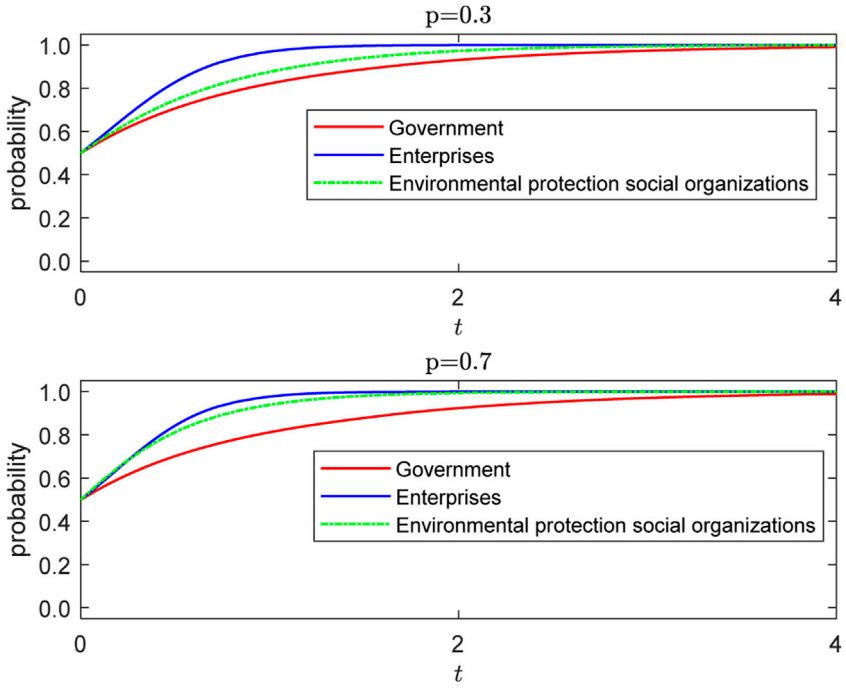

FIGURE 6
The influence of p on the game system.

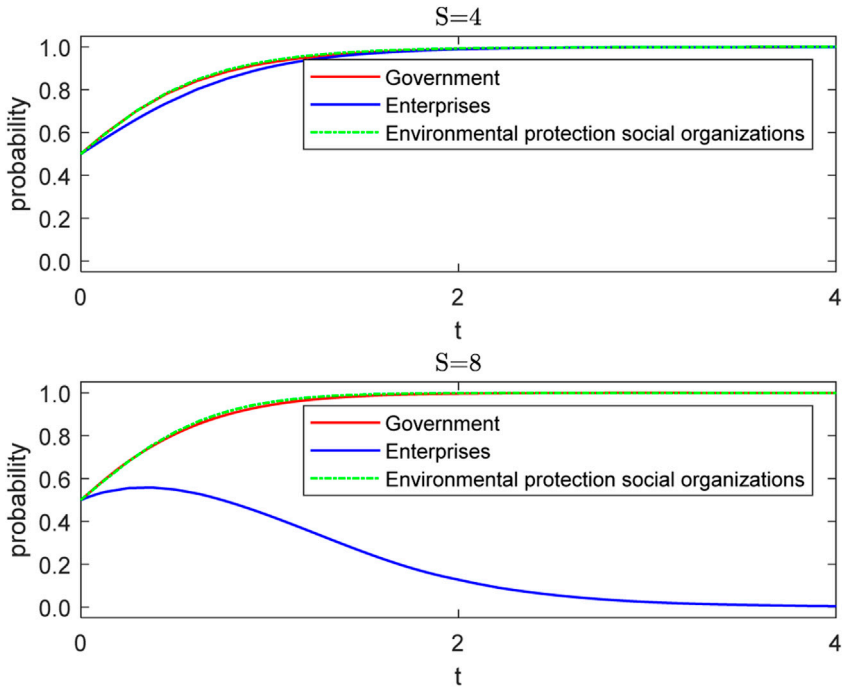

FIGURE 7
The influence of *S* on the game system.

by environmental protection social organizations to enterprises can significantly promote green technological innovation by enterprises. The reasons for this are that, by virtue of their professional advantages, such organizations can establish communication and interaction channels with enterprises on environmental protection issues, provide a wide range of types of information on cooperation, such as green resources, as well as services such as technological consulting, technological exchanges, and technological support, and

jointly promote research and development on and popularization of environmental protection technologies and management modes, so as to improve the environmental protection level and competitiveness of enterprises. In this way, environmental organizations and enterprises can jointly promote research and development on and popularization of environmental protection technologies and management models, improve the environmental protection level and competitiveness of enterprises, and jointly promote solutions to environmental problems.

4) We keep other parameters unchanged and change the probability value of public participation in supervision, as shown in Figure 6. It can be seen that with an increase in the probability of public supervision, the probability of environmental protection social organizations choosing positive strategies can be significantly increased. The reason is that the public has a strong willingness to participate, and will pay attention to the relevant messages or use of the independent platform or application of environmental protection social organizations to increase their activity, so as to bring good benefits and public favor to environmental protection social organizations, so as to promote enterprises to regulate their behavior to a certain extent.
5) We keep other parameters unchanged and change the value of reputation loss, as shown in Figure 7. It can be seen that reputation loss has a threshold value. If it exceeds a certain threshold value, the supervision will be ineffective, the behavior of the enterprise will be over constrained, the enterprise will lose confidence, and it will be easy to ignore the negative feedback brought by reputation. Keeping increases in reputation loss within an acceptable range can help avoid enterprises attracting a negative image due to an accident, which will lead to the loss of some good cooperation resources. Therefore, the enterprise chooses environmental compliance and fully improves its level of environmental self-discipline.

5 Conclusion

In the context of modern digital technology, in order to explore an effective path for collaborative supervision of corporate green behavior by multiple agents, a tripartite game model between the government, enterprises, and environmental protection social organizations was constructed from the perspective of evolutionary game theory.

5.1 Research conclusion

The impact of participating agent strategies was analyzed numerically, and the key factors affecting the ideal state were explored and simulated. The main conclusions and insights of this research are as follows: 1) An increase in government information disclosure can effectively constrain the behavior of enterprises, causing them to face certain losses of reputation. However, an excessive increase in loss of reputation can easily lead to the "complete rough" management of enterprises, which is not conducive to enterprises carrying out green innovation; the information disclosure can transmit environmental information to the public and environmental protection social organizations in a timely manner to reduce the information gap, and promote the formation of multi-dimensional common governance. 2) Big data regulation can effectively help the government save on costs and improve the accurate identification and real-time monitoring of enterprises that cause pollution without using green technology. It can significantly promote the evolution of all parties to the ideal state and improve the effectiveness of regulation. 3) Environmental social organizations provide enterprises with the necessary resource supports to significantly promote the improvement of enterprises' green technology innovation level. 4) Increased willingness of the public to participate in environmental supervision can enhance the interaction between the public and environmental social organizations, prompting environmental social organizations to actively carry out environmental protection activities and increase public goodwill and popularity, which will have a positive effect on the evolutionary results.

5.2 Policy enlightenment

To promote green innovation by enterprises, based on the research results, this paper puts forward the following recommendations: 1) The government should make reasonable increases in its supervision and enforcement of enterprise subsidies and penalties and guide more social resources into enterprise development in a timely manner. In addition, the government should enhance the development of smart government, promote the use of big data platforms in a wide range of areas, and boost the capacity for digital environmental monitoring. Additionally, it is essential to improve local governments' information disclosure systems in order to encourage enterprises to implement green technologies. 2) On the one hand, enterprises need to actively seek sustainable cooperation from environmental social organizations. On the other hand, enterprises must disclose environmental information in accordance with the law and behave in an environmentally responsible manner, thus allowing them to avoid high environmental penalties and negative environmental evaluations. 3) Environmental protection social organizations should utilize their professional advantages and establish a link to government regulations. Meanwhile, they should also strengthen cooperative relationships with enterprises and provide external motivation to facilitate enterprises' sustainable development. In addition, it is necessary for such organizations to use new media platforms in their operations. Various environmental activities are now available on such platforms. It is possible to interact positively with the public using these platforms and to increase the awareness of green behavior among enterprises.

5.3 Research limitations and future issues

Although the results of this study are reasonable and meaningful, there are still some limitations and deficiencies that we need to acknowledge. First, the tripartite model constructed in this paper is not comprehensive enough as it only selects the government and environmental social organizations and takes the public as an exogenous variable. Corporate green behavior involves

many stakeholders, making it an intricate process requiring the participation of numerous parties in a synergistic manner. Future research on this topic could include additional subjects, such as media and financial institutions, in order to explore the influence mechanisms of multiple subjects on the green development of enterprises at different levels. Second, this study has not explored the interaction mechanism between the public and other subjects deeply enough. We have only considered the interaction between the public and environmental social organizations, and our scenarios are not sufficiently comprehensive. Therefore, more scenarios and deeper discussions are needed in the future research. We plan to address the gaps mentioned above in future studies.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

HH: Conceptualization, Methodology, Writing-original draft. YW: Programming, Data analysis, Reviewing and editing.

Funding

The authors declare financial support was received for the research, authorship, and/or publication of this article. This project was supported in part by National Social Science Foundation of China (23BJY191), Natural Science Foundation of Heilongjiang Province (LH 2022G014), and Social Science Foundation of Heilongjiang Province Foundation of China (20GLB114).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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