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From a long-term dynamic perspective: how should internal carbon pricing be implemented?

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Internal carbon pricing has the potential to positively influence enterprises' carbon emissions. However, the strategies for implementing internal carbon pricing for enterprises and internal organizations remain unclear. In this study, employing a differential game research methodology, we design three implementation strategies for internal carbon pricing from a dynamic time perspective. Through comparative research and numerical analysis of these three different strategies' effects on the changes in enterprise carbon emission reduction and goodwill, we find that for both enterprises' carbon emission reduction and goodwill, Model C (implementing secondary investment for internal carbon fee collection) is optimal when the proportion of internal organizational revenue allocation is high and the proportion coefficient of internal carbon fee collection is low. When the proportion coefficient of internal carbon fee collection meets certain conditions, it makes the total profit of system under model C (implementing secondary investment for internal carbon fee collection) larger than the other two strategies. Due to short-sighted behavior, both enterprises' profits and carbon emissions gradually decrease, leading to the internal carbon prices of enterprises under the three strategies will approach a stable value.

KEYWORDS

internal carbon pricing, differential game, goodwill, enterprise carbon reduction emissions, carbon emission

1 Introduction

In recent years, China has proposed to actively implement the national independent contribution target and action plan for peaking carbon emissions in addressing climate change by 2030 and has formulated a system that focuses on carbon intensity control, supplemented by total carbon emission control, to support local and key industries and enterprises with necessary conditions to take the lead in achieving carbon emission peaks. While enterprises bear the responsibility of reducing greenhouse gas emissions and environmental management, their profit-oriented economic nature requires them to optimize their economic interests while taking relevant carbon emission reduction strategies.

Currently, carbon reduction mechanisms in enterprises can be divided into two types (Peng et al., 2022; Zhang and Meng, 2022): one is the administrative directive-based mechanism formed by the government's imposition of carbon taxes, the establishment of carbon emission trading agencies, and the promulgation of carbon emission trading laws and regulations, which has been widely studied and accepted by many scholars. The other is the internal control self-initiated carbon reduction mechanism formed by employee incentives, financial methods, etc., but relatively less researched (Zhu et al., 2021). The achievement of carbon reduction goals cannot rely solely on administrative directive-based

TABLE 1 Comparison of research content.

	Executive ordered emission reductions	Dynamic angle	Internal carbon pricing	Comparative analysis of carbon reduction strategies
Zhao Liming et al. (Zhao et al. (2016)	Y	Y	N	Y
Zhao Daozhi et al. (Zhao et al. (2016)	Y	Y	N	Y
Hou Qiang et al. (Hou, Guan (2020)	Y	Y	N	N
Nuno Bento et al. (Bento and Gianfrate (2020); Bento, Gianfrate (2021)	N	N	Y	N
Alexander R. Barron et al. (Barron, Parker (2020)	N	N	Y	N
Franziska Riedel et al. (Riedel, Gorbach (2021)	N	N	Y	N
Our study	N	Y	Y	Y

In the table Y represents "Yes" and N represents "No".

TABLE 2 Description of symbols.

Symbol	Definition
e_D	Carbon emissions of internal organizations
b	Elasticity coefficient of internal carbon price
a	Base carbon emissions of internal organizations
$p(t)$	Internal carbon price
$e_1(t)$	carbon emission
$L(t)$	Degree of effort to reduce emissions
μ_1, μ_2	Cost coefficient for corporate carbon emissions, cost coefficient for internal organization's degree of effort to reduce emissions
$R(t)$	Carbon reduction emissions
r	Initial carbon reduction emissions
η	The influence coefficient of internal carbon price on enterprises' carbon emissions
ω	The influence coefficient of the degree of effort to reduce emissions on enterprises' carbon emissions
ξ	Natural decay rate of enterprises' carbon reduction emissions
g	Initial goodwill
$\bar{e}$	Enterprise carbon quota
τ	Coefficient of the impact of the difference between enterprises' carbon emission intensity and enterprise carbon quota on goodwill
γ	Coefficients for the effect of internal carbon price on enterprises' goodwill
β	Coefficient of influence of internal organization's carbon emission reduction efforts on goodwill
σ	The natural decay rate of enterprises' goodwill
$\alpha_i > 0$ $(i = 1, 2, 3, 4)$	Represent the influence coefficient of goodwill on profit, the influence coefficient of enterprises' carbon reduction emissions on profit, and the influence coefficient of enterprises carbon emission on profit, respectively
π_e, π_D	The earnings ratio of enterprises and enterprises internal organization
ρ	Discount Rate
θ	Ratio of emission reduction cost sharing

mechanisms but must be combined with other carbon reduction strategies (Chang and Wang, 2010; Ding et al., 2010; Sun et al., 2014; Lu et al., 2019). There is a growing trend for enterprises to internalize carbon pricing to better cope with the threat posed by the growing "carbon risk" (such as supply chain transportation risks caused by extreme weather damage and financial risks arising from

TABLE 3 Table on decisions.

Internal carbon fee collection without secondary input		Internal carbon fee collection with secondary input
Without emission reduction cost-sharing	With emission reduction cost-sharing	Model C (Subsequent section marked with C)
Model N (Subsequent section marked with N)	Model S (Subsequent section marked with S)	

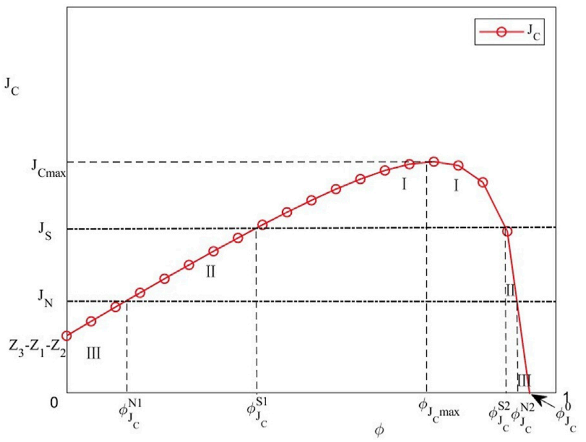

FIGURE 1
Relationship between J_C and J_S and J_N.

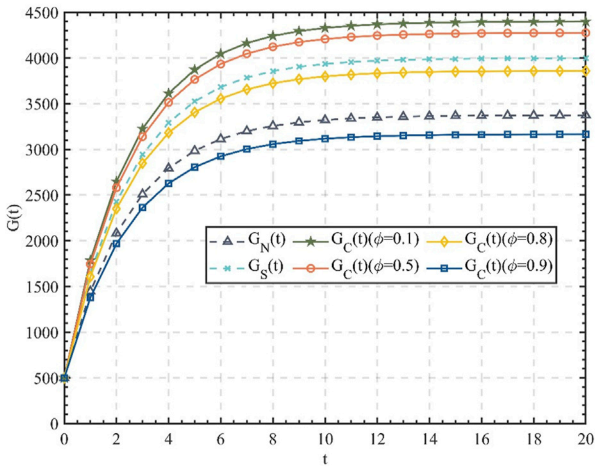

FIGURE 3
The optimal trajectory of enterprises' goodwill.

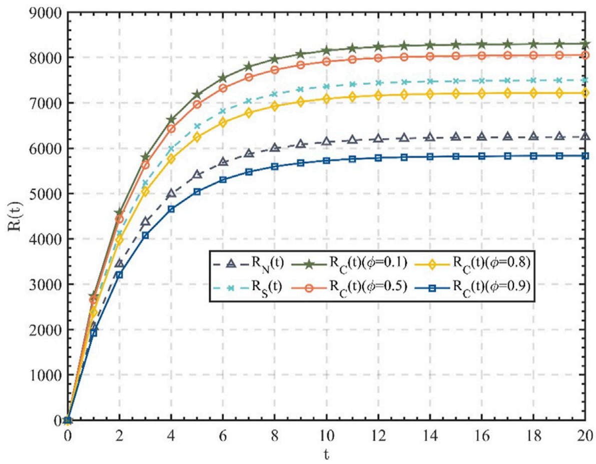

FIGURE 2
The optimal trajectory of enterprises' carbon reduction.

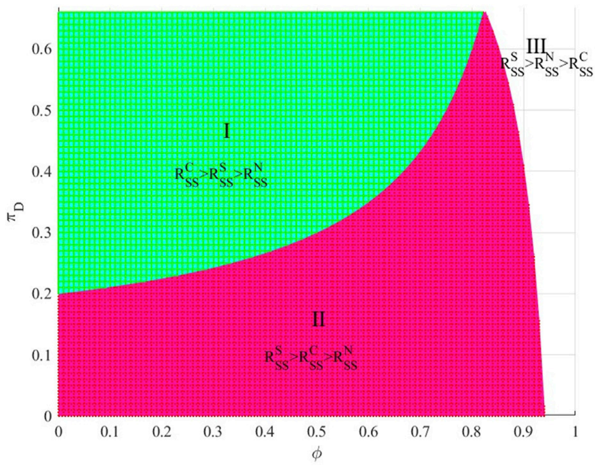

FIGURE 4
The optimal strategies for carbon emission reduction under different conditions of π_D and ϕ.

it). For example, Volvo Car Group CEO Hanken Samuelsson signed the Glasgow Coupe Net Zero Declaration at COP26. He set internal carbon pricing within the business at a charge of SEK 1,000 per tonne of CO2 emissions to reduce carbon emissions in order to achieve the goal of becoming a global benchmark company for zero climate load by 2040 (Liu and Cao, 2023). As part of an internally controlled, self-directed carbon reduction mechanism, internal carbon pricing is seen as an efficient, flexible, and cost-saving carbon reduction management tool. Its implementation not only brings clear cost-sharing responsibilities to enterprises and internal organizations but also enhances their competitive advantages in the future low-carbon economy, in line with Porter's statement that "appropriate environmental regulation can encourage enterprises to engage in more innovative activities, thereby offsetting corresponding costs and enhancing their profitability". To address the shortcomings of previous studies, this paper takes carbon emission reduction as the key state variable and goodwill as another state variable to avoid the "carbon risk" crisis and survive

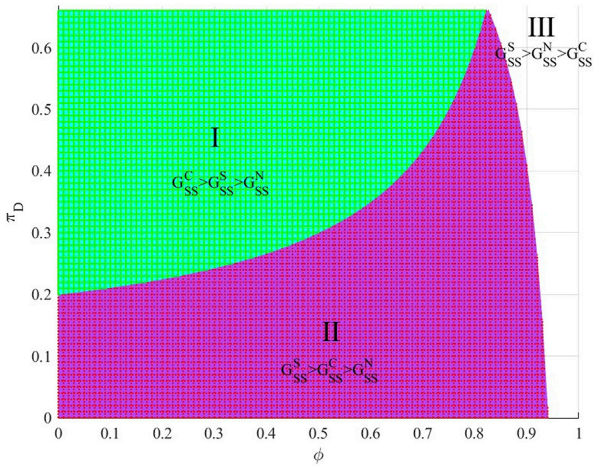

FIGURE 5
The optimal strategies for enterprises' goodwill under different conditions of π_D and ϕ.

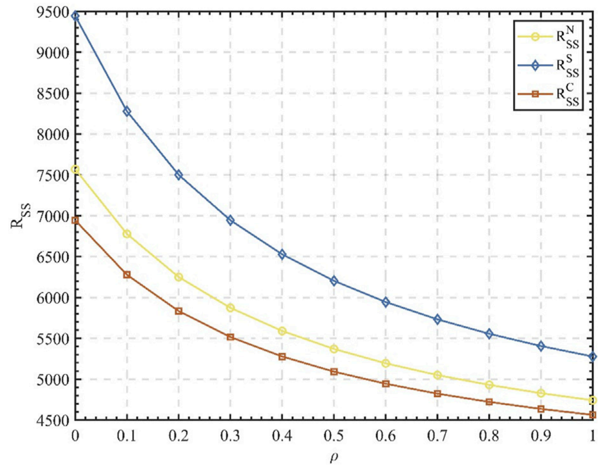

FIGURE 7
The impact of ρ on enterprises' carbon reduction.

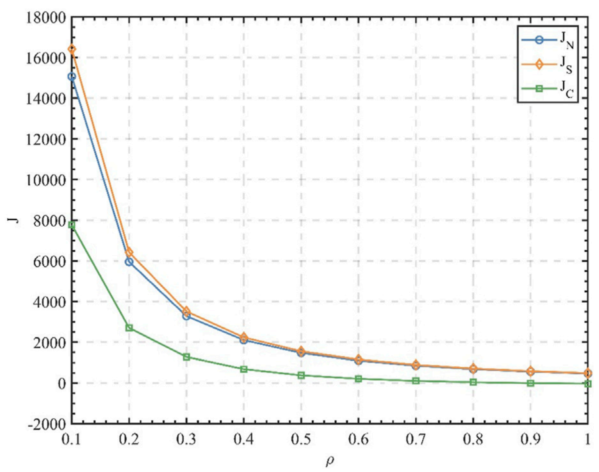

FIGURE 6
The impact of ρ on the total profit of the system.

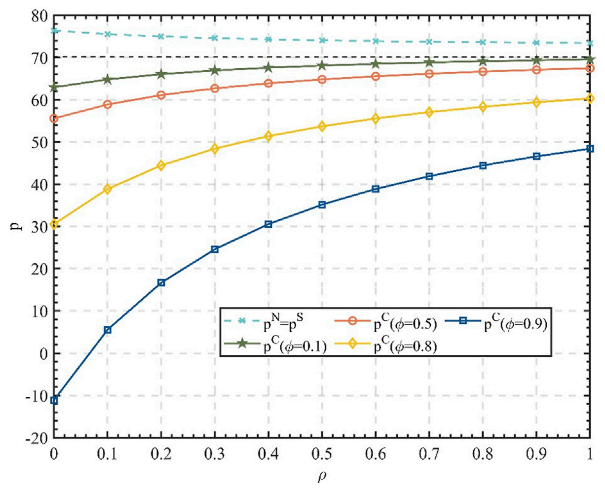

FIGURE 8
The impact of ρ on the internal carbon price.

better intangible assets (Kuo and Chang, 2021). Therefore, in this paper, we take corporate carbon emission reduction and corporate goodwill as two state variables to avoid the crisis of "carbon risk" and to survive better intangible assets. Then, we systematically analyze the combined effects of implementing different internal carbon pricing strategies on these two state variables. Finally, the implementation strategy suggestions are given, which will be of great significance and practical value.

2 Literature review

The literature review of this paper consists of two main aspects: the use of differential games in carbon emission reduction research and research related to internal carbon pricing.

2.1 Application of differential games in carbon emission reduction research

Differential game theory is a dynamic game theory in which multiple participants in a system continuously optimize their respective goals over a continuous period. It has been widely used by many scholars to study the first type of carbon reduction mechanism of enterprises. For instance, Zhao et al. (2016) investigated low-carbon development mechanisms that stimulate enthusiasm among local governments and enterprises based on social effects and constructed a political-enterprise dynamic differential game model for carbon emission reduction under two game scenarios. The analysis results showed that local governments providing support to enterprises can promote carbon emission reduction and thus drive the development of regional low-carbon

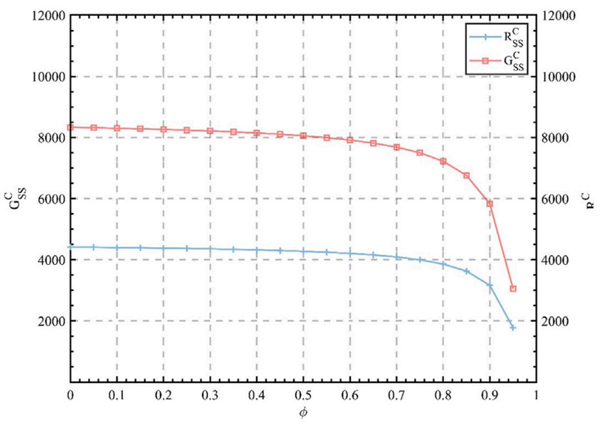

FIGURE 9
The impact of ϕ on carbon emissions reduction and goodwill.

economies. Wei and Wang (2021) constructed a differential game model based on the interactive mechanism between the government and enterprises to examine the mutual promotion effect between carbon emission reduction technology innovation by enterprises and government regulation. Mao and Wang (2022) used local enterprises in developing countries along the "Belt and Road" as subjects to construct a differential game model and studied the effect of investment and emission reduction with the promotion of enterprises in carbon emission reduction, low-carbon infrastructure investment, and low-carbon products. In addition to the above researchers who used differential game theory to study carbon emission reduction in political-enterprise relationships, it has also been widely applied in the study of carbon emission reduction in supply chain systems. Zhao et al. (2016) considered the intertemporal nature and low-carbon demand characteristics of emission reduction cooperation, achieving emission reduction and profit improvement for supply chain systems and enterprise members. Hou et al. (2020) constructed a differential game model under two mechanisms of a carbon trading system and emission reduction cost-sharing contract, considering the impact of consumer low-carbon preferences and uncertainty on carbon emission reduction behavior, and investigated the dynamic investment decision-making problem of emission reduction technology for manufacturers and retailers. Sun et al. (2020) considered the lag time of emission reduction technology and consumer low-carbon preferences, constructed a differential game model for manufacturers and suppliers in the supply chain, and studied the problem of carbon emissions transfer and reduction among enterprises. Most of the above research is based on the first type of administrative directive emission reduction mechanism, and revolves around the construction of carbon reduction differential game models for political-enterprise relationships and supply chain systems.

2.2 Internal carbon pricing

Previous scholars have mainly focused on the effectiveness of internal carbon pricing, shadow pricing, and implicit pricing methods in the daily carbon reduction management process of enterprises (Harpankar, 2019). Based on this foundation, researchers have also studied the driving factors for the use of internal carbon pricing (Aldy, 2019; Ben-Amar et al., 2022), to demonstrate its positive impact on investment evaluation, risk management, and strategic planning, which effectively prevent "carbon risk" from being eliminated by future markets. In addition, Bento and Gianfrate (2020); Bento et al. (2021) believe that national climate policies, national development, industry, and corporate management largely determine the use of internal carbon pricing. In terms of research on the application of internal carbon pricing, foreign scholars such as Oliver Gregor Gorbach first summarized the motivation for using internal carbon pricing and different methods of internal carbon pricing, described the impact of internal carbon pricing, and identified implementation obstacles, producing a process flowchart for identifying internal carbon pricing implementation (Gorbach et al., 2022). They then compared the internal carbon price with the potential regulatory carbon price in different countries using different optimization models and analyzed the differences in internal carbon prices in different countries (Gorbach et al., 2021). Finally, in the context of energy carriers, they compared the robustness of uncertain internal carbon prices in energy systems. In addition to its application in energy systems (Gorbach and Thomsen, 2022), scholars have also studied the application of internal carbon pricing in the education industry. For example, Barron et al. (2020); Lee and Lee (2022), studied the potential impact of internal carbon pricing on carbon reduction in higher education institutions, to illustrate the main benefits of internal carbon pricing in expanding campus carbon neutrality initiatives, and to discuss how schools and other institutions can use internal carbon pricing to improve the climate. However, enterprises face certain barriers in implementing internal carbon pricing, as discussed by Riedel et al. (2021), who explore the reasons why German companies do not adopt internal carbon pricing mechanisms, particularly due to the severe challenges that small German companies face in mobilizing the financial, technological, and informational resources required for internal carbon pricing implementation.

We use Table 1 to show the differences between our study and existing studies.

According to the combing of the above literature and Table 1, it can be found that most scholars have conducted research on enterprises' carbon reduction based on the first type of administrative directive emission reduction mechanism. Research on internal carbon pricing within enterprises is conducted from the perspective of static case studies such as concept definition and driving factors, with few scholars studying and designing internal carbon pricing strategies for enterprises, and lacking specific analysis of the impact of internal carbon pricing strategies on carbon reduction. Building on the models for enterprises' carbon reduction and the background of internal carbon pricing described in the literature above, this paper employs differential game theory to construct three-game strategies for implementing internal carbon pricing and analyzes the long-term dynamic impact of the three strategies on corporate carbon reduction and corporate reputation.

10.3389/fenrg.2023.1304272

3 Model assumptions

In this paper, we consider the internal carbon fee as the implementation strategy among the three methods of internal carbon pricing for enterprises. Enterprises need to impose actual internal carbon fees on their internal organizations, thus considering the internal organizations as the recipients of the internal carbon pricing strategy, while the enterprises as the implementers. The objective of this system is to achieve a balance of power, responsibility, and interests among relevant stakeholders through internal control mechanisms within the enterprise. It aims to enhance the cooperative capabilities of all parties involved, reduce operational risks for the enterprise, and make the achievement of expected carbon emission reduction goals more predictable. In this section, we list the symbols applied in this study as well as the assumption statements.

3.1 Symbols

The symbols applied in this paper are shown in Table 2:

3.2 Assumption statement

Assumption 1: When considering the impact of internal carbon pricing on carbon emissions, an increase in carbon price will lead to a reduction in carbon emissions from internal organizations, and *vice versa*. Drawing on the findings from Ma and Kuo (2021), this negative correlation can be expressed as a linear equation, as shown in Eq. 1.

$$e_D = a - bp(t) \tag{1}$$

In the equation, e_D represents the carbon emissions from internal organizations, where b is the elasticity coefficient of internal carbon pricing ($b > 0$), and is a the baseline carbon emissions from internal organizations ($a > 0$). The internal carbon price per ton of carbon emissions is denoted as $p(t)$. Accordingly, the carbon cost of internal organizational emissions can be expressed as the Eq. 2:

$$C_1(t) = p(t)e_D = p(t)\left(a - bp(t)\right) \tag{2}$$

Assumption 2: Drawing on the literature (Xu and Tan, 2021; Zheng et al., 2021), the cost of producing products for the enterprise, $C_2(t)$, is related to its carbon emissions, $e_1(t)$, and the increasing amplitude is gradually rising. Considering this convexity feature, we assume that they have a quadratic function relationship as the Eq. 3:

$$C_2(t) = \frac{1}{2}\mu_1 e_1{}^2(t) \tag{3}$$

Drawing on the literature (Zhao et al., 2016; Zhang et al., 2018), consider internal organizations to measure their abatement efficiency in terms of abatement effort $L(t)$ in conducting daily production processes, such as whether energy consumption per unit of product is reduced, whether raw materials are fully utilized, and the efficiency of pollutant treatment. Assuming internal organization reduces emission costs $C_3(t)$ is related to the emission reduction effort $L(t)$, thus there is also a quadratic function relationship as shown in Eq. 4:

$$C_3(t) = \frac{1}{2}\mu_2 L^2(t) \tag{4}$$

where $\mu_1 > 0$, $\mu_2 > 0$, they are the cost coefficients of carbon emissions of enterprises and the cost coefficients of internal organizational effort to reduce emissions, respectively.

Assumption 3: Drawing on the literature (Lee and Lee, 2022), it is assumed that enterprises' carbon emission reduction $R(t)$ is dynamic over time, and its dynamics are jointly influenced by the enterprises' internal carbon price $p(t)$ and the degree of internal organizational carbon reduction effort $L(t)$. The differential equation is shown in Eq. 5:

$$\dot{R}(t) = \eta p(t) + \omega L(t) - \xi R(t) \tag{5}$$

where $R(t)$ is the carbon emission reduction of enterprises and the initial carbon emission reduction $R(0)=r \geqslant 0$. $\eta > 0$ is the influence coefficient of the internal carbon price on the carbon emission reduction of enterprises, indicating the influence of raising the internal carbon price on enterprises' carbon emission reduction. $\omega > 0$ is the impact coefficient of the degree of emission reduction effort on the carbon emission reduction of enterprises. $\xi > 0$ is the natural decay rate of the carbon emission reduction of enterprises.

Assumption 4: The adoption of internal carbon pricing by enterprises for self-regulation and the level of carbon emission reduction efforts within their internal organization can have a positive impact on the enterprises' reputation, aiding in carbon risk management and planning. Building upon the findings of reference (Nerlove and Arrow, 1962), the goodwill model is modified to obtain the following differential equation, as shown in Eq. 6:

$$\dot{G}(t) = \gamma p(t) + \beta L(t) - \tau\left(e_1(t) - \bar{e}\right) - \sigma G(t) \tag{6}$$

where $G(t)$ is the enterprises' goodwill, and the initial goodwill $G(0) = g \geqslant 0$. $\bar{e}$ is the carbon allowance of enterprises, $e_1(t) - \bar{e}$ indicates the difference between carbon emission and carbon allowance of enterprises. If the difference is greater than zero, it indicates a negative impact on goodwill. If the difference is less than 0, it indicates a positive impact on goodwill. $\tau > 0$ denotes the influence coefficient of the difference between carbon emission intensity and carbon allowance of enterprises on goodwill. $\gamma > 0$ is the influence coefficient of the internal carbon price on enterprises' goodwill, indicating the efficiency of the impact of increasing internal carbon prices on enterprises' goodwill. $\beta > 0$ is the influence coefficient of the degree of internal organizational carbon emission reduction effort on goodwill. $\sigma > 0$ is the natural decay rate of enterprises' goodwill.

Assumption 5: Carbon dioxide, as a by-product of production, has a relationship between its emissions and enterprises' benefits. Drawing on the models in the literature (Jiang and You, 2019; Xu and Tan, 2021) on the relationship between enterprises' production benefits and pollution emissions, and considering that enterprises' profits are influenced by goodwill and carbon emission reductions, the enterprise benefits are expressed as Eq. 7:

$$B(t) = \alpha_1 G(t) + \alpha_2 R(t) + \alpha_3 e_1(t) - \alpha_4 {e_1}^2(t) \tag{7}$$

where $\alpha_i > 0$ $(i = 1, 2, 3, 4)$ denotes goodwill, enterprises' carbon emission reduction, and the influence coefficient of enterprises' carbon emission on profit, respectively.

Assumption 6: The profits of enterprises and their internal organizations are distributed between them, assuming that they are allocated according to the benefit allocation ratio π_e, π_D $(\pi_E + \pi_D = 1)$, respectively. In continuous infinite time, both have the same discount rate ρ $(\rho > 0)$, and both seek to maximize their interests in the future.

4 Model construction

The internal organizations are considered the controlled objects for the implementation of internal carbon pricing, and the enterprises are the controlling subject. The objective of this system is to achieve a balance of power, responsibility, and interests among the relevant stakeholders through internal control, enhancing their cooperation and reducing their operational risks. This, in turn, leads to a more predictable achievement of the expected carbon emission reduction targets. Building upon the assumptions and descriptions outlined in the introduction, to better verify the emission reduction effect of implementing internal carbon pricing, three decision models in the following decision table are considered, as shown in Table 3:

In this system, two game subjects are defined: enterprises and internal organizations. There are four control variables: $e_1(t) \geqslant 0$, $L(t) \geqslant 0$, $p(t) \geqslant 0$, $0 \leqslant \theta \leqslant 1$, and two state variables: $G(t) \geqslant 0$, $(t) \geqslant 0$.

4.1 Model N

In this model, enterprises will charge a complete internal carbon fee to internal organizations without implementing secondary investment, and internal organizations will not receive any cost subsidies. As a result, the cost-sharing ratio for emission reduction $\theta = 0$. Both enterprises and internal organizations choose to maximize profits under the constraints of dynamic changes in goodwill and carbon reduction emissions. According to the optimal control theory, this model represents an optimal control problem with an integral-type performance index, fixed terminal time, and free terminal state. Drawing on the literature (Li et al., 2014; Dye, 2020; Shi and You, 2023), the problem can be solved using Pontryagin's maximum principle. The Pontryagin maximum principle is an important principle in classical control theory. It points out that the optimal solution of the control problem can be obtained by variable substitution and Hamiltonian function construction under certain conditions. The basic idea of Pontryagin's maximum principle is that the optimal state orbit of an optimal control problem can be characterized by a Hamilton system with a margin problem. The objective functions in the model are shown in Eq. 8 and Eq. 9:

$$\max_{p,e_1} J_E = \int_0^\infty e^{-\rho t}\left(\pi_e\left(\alpha_1 G(t) + \alpha_2 R(t) + \alpha_3 e_1(t) - \alpha_4 {e_1}^2(t)\right) + p(t)(a - bp(t)) - \frac{1}{2}\mu_1 e_1^2(t)dt\right) \tag{8}$$

$$\max_{L} J_D = \int_0^\infty e^{-\rho t}\left(\pi_D\left(\alpha_1 G(t) + \alpha_2 R(t) + \alpha_3 e_1(t) - \alpha_4 {e_1}^2(t)\right) - p(t)(a - bp(t)) - \frac{1}{2}\mu_1 L^2(t)dt\right) \tag{9}$$

$$s.t.\dot{R}(t) = \eta p + \omega L - \xi R, R(0) = r \geqslant 0$$

$$s.t.\dot{G}(t) = \gamma p + \beta L - \tau(e_1 - \bar{e}) - \sigma G, G(0) = g \geqslant 0$$

Proposition 1: In model N:

(1) The equilibrium strategies for the internal carbon price, internal organizational emission reduction efforts, and the enterprises' carbon emissions are defined as follows:

$$L^N = \frac{\pi_D\left(\frac{\beta\alpha_1}{\rho+\sigma} + \frac{\omega\alpha_2}{\xi+\rho}\right)}{\mu_2},\quad p^N = \frac{a + \frac{\gamma\pi_e\alpha_1}{\rho+\sigma} + \frac{\eta\pi_e\alpha_2}{\xi+\rho}}{2b},\quad e_1^N = \frac{\pi_e\left(-\frac{\tau\alpha_1}{\rho+\sigma} + \alpha_3\right)}{2\pi_e\alpha_4 + \mu_1}$$

To ensure positive carbon emissions, where: $\alpha_3 > \frac{\tau\alpha_1}{\rho+\sigma}$.

(2) The optimal trajectories of enterprises' goodwill and carbon emission reductions, respectively, are:

$$G^N(t) = e^{-t\sigma}g - G_{SS}^N e^{-t\sigma} + G_{SS}^N$$
$$R^N(t) = e^{-t\xi}r - e^{-t\xi}R_{SS}^N + R_{SS}^N$$

Where, $G_{SS}^N = \frac{p^N\gamma + \tau\bar{e} - \tau e_1^N + \beta L^N}{\sigma} > 0$, $R_{SS}^N = \frac{p^N\eta + \omega L^N}{\xi} > 0$, and G_{SS}^N, R_{SS}^N are the stabilization value of the goodwill and the stabilization value of carbon emission reduction at $t \to +\infty$, respectively.

(3) The profit of system members and the total profit of the system are respectively:

$$J_N^E = \frac{2p^N(a - bp^N) + \frac{2(g\rho + \sigma G_{SS}^N)\pi_e\alpha_1}{\rho+\sigma} + \frac{2\pi_e(r\rho + \xi R_{SS}^N)\alpha_2}{\xi+\rho} + 2e_1^N\pi_e\alpha_3 - (e_1^N)^2(2\pi_e\alpha_4 + \mu_1)}{2\rho}$$

$$J_N^D = \frac{2p^N(-a + bp^N) + 2\pi_D\left(\frac{(g\rho + \sigma G_{SS}^N)\alpha_1}{\rho+\sigma} + \frac{(r\rho + \xi R_{SS}^N)\alpha_2}{\xi+\rho} + e_1^N(\alpha_3 - e_1^N\alpha_4)\right) - (L^N)^2\mu_2}{2\rho}$$

$$J_N = J_N^E + J_N^D$$

Proposition 1 proof can be found in Supplementary Appendix SA1.

Corollary 1: Based on Proposition 1, the following conclusions can be drawn:

(1) $\frac{\partial L^N}{\partial \pi_D} = \frac{\left(\frac{\beta\alpha_1}{\rho+\sigma} + \frac{\omega\alpha_2}{\xi+\rho}\right)}{\mu_2} > 0, \frac{\partial L^N}{\partial \rho} = \frac{\pi_D\left(-\frac{\beta\alpha_1}{(\rho+\sigma)^2} - \frac{\omega\alpha_2}{(\xi+\rho)^2}\right)}{\mu_2} < 0$

This indicates that the level of emission reduction efforts within internal organizations is positively correlated with the distribution ratio of profits and inversely correlated with the discount rate. The greater the share of profits allocated to internal organizations, the lower the discount rate, which encourages internal organizations to actively engage in emission reduction efforts.

(2) $\frac{\partial e_1^N}{\partial \pi_e}=\frac{(-\tau\alpha_1+(\rho+\sigma)\alpha_3)\mu_1}{(\rho+\sigma)(2\pi_e\alpha_4+\mu_1)^2}>0,\ \frac{\partial e_1^N}{\partial \rho}=\frac{\tau\pi_e\alpha_1}{(\rho+\sigma)^2(2\pi_e\alpha_4+\mu_1)}>0,$

$$\frac{\partial p^N}{\partial \rho}=\frac{-\frac{\gamma\pi_e\alpha_1}{(\rho+\sigma)^2}-\frac{\eta\pi_e\alpha_2}{(\xi+\rho)^2}}{2b}<0,\ \frac{\partial p^N}{\partial \pi_e}=\frac{\frac{\gamma\alpha_1}{\rho+\sigma}+\frac{\eta\alpha_2}{\xi+\rho}}{2b}>0,\frac{\partial p^N}{\partial a}=\frac{1}{2b}>0$$

This indicates that the internal carbon price is inversely proportional to the discount rate and directly proportional to the distribution ratio of enterprises' profits and the baseline carbon emissions of internal organizations. Furthermore, the enterprises' carbon emissions are directly proportional to the distribution ratio of profits and the discount rate. It can be observed that for enterprises with higher carbon emission demands, a higher internal carbon price is required to constrain them.

(3) It can be deduced from $\frac{\partial G^N(t)}{\partial t}=e^{-t\sigma}\sigma(-g+G_{SS}^N)$ that when $g<G_{SS}^N$, enterprises' goodwill monotonically increases over time and gradually converges to the steady-state value of enterprises' goodwill. Conversely, when $g>G_{SS}^N$, enterprises' goodwill monotonically decreases over time and converges to the steady-state value of enterprises' goodwill. The optimal trajectory of carbon reduction $R^N(t)$ follows a similar pattern, which is not elaborated here.

4.2 Model S

In this model, enterprises continue to fully charge internal carbon fees without secondary investments. However, as enterprises hold a leadership position and aim to incentivize internal organizations to reduce emissions, a cost subsidy is considered to share the cost of their emission reduction efforts, denoted by the cost allocation ratio $\theta \neq 0$. In this scenario, both enterprises and internal organizations seek to maximize their interests, leading to a two-stage Stackelberg game between them. The decision-making process involves the following stages: In the first stage, enterprises determine the internal carbon price p, carbon emissions e_1, and the cost allocation ratio θ. In the second stage, based on the enterprises' chosen strategy, internal organizations decide on their carbon reduction efforts L. The Stackelberg Game is a two-stage complete information dynamic game where the time of the game is sequential. The main idea is that both sides are choosing their own strategies based on the possible strategies of the other side to ensure that they maximize their benefits under the other side's strategy, so as to achieve Nash equilibrium. Drawing on the construction of the Stackelberg game model in the literature (Zhao et al., 2016; Xu and Tan, 2021), the objective function under this model is as follows:

$$\max_{p,e_1} J_E=\int_0^\infty e^{-\rho t}\left(\pi_e\left(\alpha_1 G(t)+\alpha_2 R(t)+\alpha_3 e_1(t)-\alpha_4 {e_1}^2(t)\right)\right.$$
$$\left.+\ p(t)\left(a-bp(t)\right)-\frac{1}{2}\mu_1 e_1^2(t)-\ \theta\frac{1}{2}\mu_2 L^2(t)\right)dt$$

$$\max_{L} J_D=\int_0^\infty e^{-\rho t}\left(\pi_D\left(\alpha_1 G(t)+\alpha_2 R(t)+\alpha_3 e_1(t)-\alpha_4 {e_1}^2(t)\right)\right.$$
$$\left.-p(t)\left(a-bp(t)\right)-(1-\theta)\frac{1}{2}\mu_2 L^2(t)\right)dt$$
$$s.t.\dot{R}(t)=\eta p+\omega L-\xi R, R(0)=r\geqslant 0$$
$$s.t.\dot{G}(t)=\gamma p+\beta L-\tau\left(e_1-\bar{e}\right)-\sigma G, G(0)=g\geqslant 0$$

Proposition 2: In Model S:

(1) The optimal equilibrium strategies for internal carbon pricing, internal organizational efforts for emission reduction, enterprises' carbon emissions, and cost allocation ratio are as follows:

$$L^S=\frac{(\pi_D+2\pi_e)\left(\beta(\xi+\rho)\alpha_1+(\rho+\sigma)\omega\alpha_2\right)}{2(\xi+\rho)(\rho+\sigma)\mu_2},\ p^S=\frac{a+\eta\frac{\pi_e\alpha_2}{\xi+\rho}+\gamma\frac{\pi_e\alpha_1}{\sigma+\rho}}{2b}$$
$$e_1^S=\frac{\pi_e\alpha_3-\tau\frac{\pi_e\alpha_1}{\sigma+\rho}}{2\pi_e\alpha_4+\mu_1},\ \theta=1-\frac{2\pi_D}{\pi_D+2\pi_e}$$

(2) The optimal trajectories of enterprises' goodwill and carbon emission reductions are:

$$G^S(t)=e^{-t\sigma}g-G_{SS}^S e^{-t\sigma}+G_{SS}^S$$
$$R^S(t)=e^{-t\xi}r-e^{-t\xi}R_{SS}^S+R_{SS}^S$$

Where, $G_{SS}^S=\frac{p^S\gamma+\tau\bar{e}-\tau e_1^S+\beta L^S}{\sigma}>0$, $R_{SS}^S=\frac{p^S\eta+\omega L^S}{\xi}>0$ and G_{SS}^S, R_{SS}^S are the stabilization value of the goodwill and the stabilization value of carbon emission reduction at $t\rightarrow+\infty$, respectively.

(3) The profit of system members and the total profit of the system are respectively:

$$J_S^E=\frac{2p^S(a-bp^S)+\frac{2(g\rho+\sigma G_{SS}^S)\pi_e\alpha_1}{\rho+\sigma}+\frac{2\pi_e(r\rho+\xi R_{SS}^S)\alpha_2}{\xi+\rho}+2e_1^S\pi_e\alpha_3-(e_1^S)^2(2\pi_e\alpha_4+\mu_1)-(L^S)^2\theta\mu_2}{2\rho}$$

$$J_S^D=\frac{2p^S(-a+bp^S)+2\pi_D\left(\frac{(g\rho+\sigma G_{SS}^S)\alpha_1}{\rho+\sigma}+\frac{(r\rho+\xi R_{SS}^S)\alpha_2}{\xi+\rho}+e_1^S(\alpha_3-e_1^S\alpha_4)\right)+(L^S)^2(-1+\theta)\mu_2}{2\rho}$$

$$J_S=J_S^E+J_S^D$$

The proof of Proposition 2 follows a similar approach as the proof of Proposition 1 and will not be repeated here for brevity.

Corollary 2: By Proposition 2 it is known that:

(1) Only when π_D and π_e meet $0<\pi_D<\frac{2}{3},\frac{1}{3}<\pi_e<1$, enterprises will share the emission reduction costs of internal organizations.

(2) $\frac{\partial\theta}{\partial\pi_D}=-\frac{2\pi_D}{(2(1-\pi_D)+\pi_D)^2}-\frac{2}{2(1-\pi_D)+\pi_D}<0,\ \frac{\partial\theta}{\partial\pi_e}=\frac{2(1-\pi_e)}{(1+\pi_e)^2}+\frac{2}{1+\pi_e}>0$

Corollary 2 demonstrates that as rational actors with absolute dominance, enterprises are only willing to implement cost-sharing strategies for internal organizations' emission reduction when their profits meet certain conditions. Moreover, the larger the distribution of their profits, the greater the cost of emission reduction shared by enterprises.

4.3 Model C

In Model C, considering the collaborative relationship between enterprises and internal organizations, a carbon fee collection coefficient $0 \le \phi < 1$ is set, representing the portion $(1-\phi)$ that enterprises can reinvest in green technologies, low-carbon initiatives, and emission reduction incentives to enhance the synergistic willingness within internal organizations (Ma and Kuo, 2021). The objective function under this model is as follows:

$$\max J_C = \int_0^{\infty} e^{-\rho t} \left(\alpha_1 G(t) + \alpha_2 R(t) + \alpha_3 e_1(t) - \alpha_4 e_1{}^2(t) - (1-\phi) p(t)(a - bp(t)) - \frac{1}{2}\mu_1 e_1{}^2(t) - \frac{1}{2}\mu_2 L^2(t)\right) dt$$

$$s.t. \dot{R}(t) = \eta p + \omega L - \xi R, R(0) = r \geqslant 0$$

$$s.t. \dot{G}(t) = \gamma p + \beta L - \tau(e_1 - \bar{e}) - \sigma G, G(0) = g \geqslant 0$$

Proposition 3: In Model C:

(1) The optimal equilibrium strategies for enterprises' internal carbon price, the level of internal organizational effort to reduce emissions, and enterprises' carbon emissions, respectively, are:

$$L^C = \frac{\omega \frac{\alpha_2}{\xi+\rho} + \beta \frac{\alpha_1}{\sigma+\rho}}{\mu_2}, \quad p^C = \frac{-a + a\phi + \eta \frac{\alpha_2}{\xi+\rho} + \gamma \frac{\alpha_1}{\sigma+\rho}}{2b(-1+\phi)}, \quad e_1^C = \frac{\alpha_3 - \tau \frac{\alpha_1}{\sigma+\rho}}{2\alpha_4 + \mu_1}$$

(2) The optimal trajectories for enterprises' goodwill and carbon emission reduction are as follows:

$$G^C(t) = e^{-t\sigma} g - G_{SS}^C e^{-t\sigma} + G_{SS}^C$$
$$R^C(t) = e^{-t\xi} r - e^{-t\xi} R_{SS}^C + R_{SS}^C$$

Where, $G_{SS}^C = \frac{p^C\gamma + \tau\bar{e} - \tau e_1^C + \beta L^C}{\sigma} > 0$, $R_{SS}^C = \frac{p^C\eta + \omega L^C}{\xi} > 0$ and G_{SS}^C, R_{SS}^C are the stabilization value of the goodwill and the stabilization value of carbon emission reduction at $t \to +\infty$, respectively.

(3) The total profit of the system is:

$$J_C = \frac{2p^C(a - bp^C)(-1+\phi) + \frac{2(g\rho + \sigma G_{SS}^C)\alpha_1}{\rho+\sigma} + \frac{2(r\rho + \xi R_{SS}^C)\alpha_2}{\xi+\rho} + 2e_1^C\alpha_3 - (e_1^C)^2(2\alpha_4 + \mu_1) - (L^C)^2\mu_2}{2\rho}$$

The proof of Proposition 3 follows a similar approach as the proof of Proposition 1 and will not be repeated here for brevity.

Corollary 3: By Proposition 3 it is known that:

(1) $\frac{\partial p^C}{\partial \phi} = -\frac{\gamma(\xi+\rho)\alpha_1 + \eta(\rho+\sigma)\alpha_2}{2b(\xi+\rho)(\rho+\sigma)(-1+\phi)^2} < 0$

This indicates that in Model C, the coefficient of internal carbon fee collection is inversely proportional to the internal carbon price. In other words, when the actual amount of internal carbon fee collected by enterprises increases, enterprises tend to set a lower internal carbon price.

(2) There is a maximum point in the internal carbon fee collection ratio coefficient $\phi_{J_{C\max}}$ and critical value point $\phi_{J_C}^0$ $(\phi_{J_{C\max}} < \phi_{J_C}^0)$, such that when $\phi \in [0, \phi_{J_{C\max}}]$, $\frac{\partial J_C}{\partial \phi} > 0$. And when $\phi \in (\phi_{J_{C\max}}, \phi_{J_C}^0]$, $\frac{\partial J_C}{\partial \phi} < 0$, and $J_{C\max} = J_C(\phi_{J_{C\max}}) = -2\sqrt{Z_1}\sqrt{Z_2} + Z_3 > 0$

This indicates that in model C, the coefficient ϕ of internal carbon fee collection has a certain regulatory effect on the overall system profit. When the value of ϕ is small, increasing its value leads to an increase in the total system profit. Conversely, when the value of ϕ is large, increasing its value results in a decrease in the total system profit.

The proof of Corollary 3 can be found in Supplementary Appendix SA1.

From Corollary 3, it can be found that the coefficient ϕ of internal carbon fee collection in enterprises has certain practical significance for the formulation of the internal carbon price and enterprises' profits. In the following sections, we will delve into a detailed exploration of how the value of the coefficient ϕ of internal carbon fee collection influences the relevant variables in the three models.

5 Comparison and analysis

This section presents comparative analyses of the optimal equilibrium strategies of the enterprises and internal organizations, the stable values of goodwill and carbon reduction emissions, and the total profits of the system across the three models. It further investigates the impact of the range of the carbon fee collection coefficient ϕ on the stable values of goodwill and carbon reduction emissions, and overall system profits in the three models. The following conclusions are drawn:

Corollary 4: When $-\frac{\tau\alpha_1}{\rho+\sigma} + \alpha_3 > 0$, the optimal equilibrium strategies for enterprises and internal organizations under three models are compared and analyzed as follows: $L^C > L^S > L^N$, $p^S = p^N > p^C$, $e_1^C > e_1^S = e_1^N$.

According to Corollary 4, under certain conditions, the following observations can be made: In Model C, the internal carbon price of enterprises is the lowest. In Models N and S, the carbon emissions of enterprises remain constant and are lower than in Model C. In Model C, internal organizationS exhibit the highest level of effort.

Corollary 5: Comparative analysis of the stable values of goodwill and carbon emission reductions in the three models reveals the following observations:

(1) When $0 < \pi_D < 2/3$, $G_{SS}^S > G_{SS}^N$, $R_{SS}^S > R_{SS}^N$
(2) When constraint 1 is satisfied, we have $G_{SS}^C > G_{SS}^S > G_{SS}^N$. When constraint 2 is satisfied, we have $G_{SS}^S > G_{SS}^C > G_{SS}^N$. And when constraint 3 is satisfied, we have $G_{SS}^S > G_{SS}^N > G_{SS}^C$.
(3) When constraint 4 is satisfied, we have $R_{SS}^C > R_{SS}^S > R_{SS}^N$. When constraint 5 is satisfied, we have $R_{SS}^S > R_{SS}^C > R_{SS}^N$. And when constraint 6 is satisfied, we have $R_{SS}^S > R_{SS}^N > R_{SS}^C$.

The proof of Corollary 5 can be found in Supplementary Appendix SA1.

According to Corollary 5, it can be concluded that under the conditions of $0 < \pi_D < 2/3$ or $\frac{1}{3} < \pi_e < 1$, enterprises are willing to bear a certain emission reduction cost for internal organizations. In this case, the stable values of carbon emissions and the goodwill of enterprises in Model C are higher than those in Model N. Furthermore, when specific constraints are met for both ϕ and π_D, the stable values of carbon emissions and the goodwill of enterprises in Model C are higher than those in the other two scenarios.

Corollary 6: Comparative analysis of the total system profit in the three models reveals the following findings:

(1) When $0 < \pi_D < 2/3$, $J_S > J_N$
(2) Due to the varying relationships between J_C and J_S, J_N under different conditions, we provide a comprehensive analysis in Supplementary Appendix SA1. Based on the reasoning process outlined in Corollary 3, we present six figures to illustrate all six scenarios, aiding in understanding their relative magnitudes. Here we focus on Scenario 1 and discuss Figure 1.

According to Figure 1, when $J_{\mathrm{Cmax}} = -2\sqrt{Z_1}\sqrt{Z_2} + Z_3 > J_S > J_N > Z_3 - Z_1 - Z_2 > 0$ and $0 < Z_2 < \frac{J_S^2 - 2J_S Z_3 + Z_3^2}{4Z_1}$, the following relationships hold: In Region I, defined as $\phi_{J_C}^{S1} < \phi < \phi_{J_C}^{S2}$, we observe that $J_C > J_S > J_N$. Region II, defined as $\phi_{J_C}^{N1} < \phi < \phi_{J_C}^{S1}$ or $\phi_{J_C}^{S2} < \phi < \phi_{J_C}^{N2}$, the order of magnitude is $J_S > J_C > J_N$. In Region III, defined as $0 < \phi < \phi_{J_C}^{N1}$ or $\phi_{J_C}^{N2} < \phi < \phi_{J_C}^{0}$, we find that $J_S > J_N > J_C$. These findings provide valuable insights into the relative magnitudes of J_C, J_S, and J_N under different parameter conditions. The graphical representation in Figure 1 visually captures these relationships, aiding in a better understanding of the system dynamics.

The proof of Corollary 6 is shown in Supplementary Appendix SA1.

From Corollary 6, we know that when $0 < \pi_D < 2/3$, the profit of the whole system increases compared with Model S and Model N. When ϕ satisfies certain conditions, it can make the profit of the system under Model C greater than Model S and Model N.

6 Numerical analysis

The preceding content primarily analyzes the differences in various internal carbon pricing strategies from a theoretical perspective by constructing models and solving them. This section mainly uses numerical analysis to further study the impact of relevant parameters on the optimal equilibrium strategy, goodwill, carbon reduction, and total system profit and then draws conclusions. Under the conditions of $\alpha_3 > \frac{\lambda\alpha_1}{\rho+\sigma}, \frac{1}{3} < \pi_e \leqslant 1, 0 \leqslant \pi_D < \frac{2}{3}$. We assume the baseline parameters to be $\rho = 0.2, \gamma = \beta = 10, \sigma = 0.4, \pi_e = 0.5, \pi_D = 0.5, \xi = 0.4, \alpha_1 = 0.2, \alpha_2 = 0.2, \eta = \omega = 20, a = 130, b = 0.9, \tau = 1, \bar{e} = 100, \alpha_4 = \alpha_3 = 1, \mu_1 = 0.1, \mu_2 = 0.1$.

6.1 Analysis of optimal trajectories for enterprises' carbon emissions reduction and goodwill

Keeping other parameters constant, we set the initial carbon emission reduction value of enterprises as $r = 0$ and the initial goodwill value as $g = 500$, resulting in the optimal evolutionary trajectory graphs.

According to Figures 2, 3, under certain conditions, the following observations can be made: (1) The carbon emission reduction and goodwill values gradually increase in all three scenarios and eventually converge to stable values. (2) The carbon emission reduction and goodwill values in Model S are consistently higher than those in Model N throughout the evolutionary process. (3) As the internal carbon fee collection ratio coefficient ϕ increases, the stable values of carbon emission reduction and goodwill in Model C gradually decrease and eventually become lower than those in Model N. This indicates that the collection of internal carbon fees has a certain impact on the carbon emission reduction and goodwill of enterprises when implementing internal carbon pricing strategies.

According to Figures 4, 5, the following observations can be made: In Region I, we have $G_{SS}^C > G_{SS}^S > G_{SS}^N$ and $R_{SS}^C > R_{SS}^S > R_{SS}^N$. In Region II, we have $G_{SS}^S > G_{SS}^C > G_{SS}^N$ and $R_{SS}^S > R_{SS}^C > R_{SS}^N$. In Region III, we have $G_{SS}^S > G_{SS}^N > G_{SS}^C$ and $R_{SS}^S > R_{SS}^N > R_{SS}^C$. Therefore, when both the internal carbon fee ratio ϕ and the internal organizational benefit distribution ratio π_D are relatively high or low, the optimal choice for enterprises is Model S (where the internal carbon fee is not reinvested and there is cost sharing for carbon reduction). When the internal organizational benefit distribution ratio π_D is high and the internal carbon fee ratio ϕ is low, the optimal choice for enterprises is Model C (where the internal carbon fee is reinvested). This indicates that when the internal organizational benefit distribution ratio π_D is high, there is a higher motivation for carbon reduction within internal organizations. Although enterprises may have higher carbon emissions, implementing a higher internal carbon price can increase their carbon reduction emissions. On the other hand, when the internal carbon fee ratio ϕ is low, enterprises set a higher internal carbon price and allocate the higher internal carbon fee to secondary investments. This helps to increase the motivation for carbon reduction within internal organizations, thus leading to higher carbon reduction levels.

6.2 Sensitivity analysis of relevant parameters

By setting $\phi = 0.9$, we obtained Figures 6, 7. Subsequently, keeping the baseline parameters unchanged, we obtained Figures 8, 9.

Based on Figures 6, 7, the following observations can be made:

(1) As the discount rate ρ increases, both the enterprises' profit and carbon emission reduction gradually decrease. Moreover, the slopes of the curves decrease with the ρ increasing, indicating that enterprises may exhibit short-sighted behavior by focusing on maximizing short-term profits and reducing investments in carbon emission reduction.
(2) According to Figure 8, the presence of short-sighted behavior leads to a convergence of internal carbon prices across the three-game strategies, approaching a stable value. In this case, both Model N and Model S consistently exhibit higher internal carbon prices compared to Model S. This indicates that to maximize their interests, enterprises tend to choose a higher internal carbon price to maintain good carbon emission performance when the internal carbon fee is fully collected

without second investment. On the other hand, due to the second investment in internal carbon fees, which results in higher carbon emission reduction and greater efforts from the internal organization, enterprises can achieve better social goodwill. In this scenario, enterprises are inclined to choose a lower internal carbon price.

(3) Combining Figures 8, 9, it can be observed that the stable values of carbon emission reduction, enterprises' goodwill, and internal carbon price under Model C decrease continuously with an increasing internal carbon fee collection ratio, represented by ϕ. Moreover, the magnitude of this decrease becomes more pronounced at higher ϕ values. This implies that, in Model C, if enterprises collect higher internal carbon fees while neglecting secondary investments in these fees, it may affect the trust of internal organizations toward enterprises. Consequently, it would introduce more uncertainty and potentially lead to speculative behavior regarding internal organizations' carbon emission reduction efforts. Ultimately, this can impact the effectiveness of both carbon emission reduction and internal carbon pricing mechanisms implemented by enterprises.

7 Conclusion and outlook

The differential game model can accurately capture the complex interactions and game relationships between the dominant player (enterprise) and the followers (internal organization) in carbon pricing within the enterprise. Thus, it truly reflects the influence of internal organizations' willingness to collaborate on carbon pricing decisions, which makes the study closer to the actual situation. Moreover, the researchers are able to dynamically compare different internal carbon pricing strategies through the differential game model, so as to gain a deeper understanding of the impacts of different strategies on carbon emission reduction and goodwill of enterprises, and to provide more informed choices for corporate decision makers in the formulation of carbon management strategies. Finally, the model allows for the consideration of time dynamics, which reveals the changing trends of enterprise carbon emission reduction and goodwill during the evolution process, providing valuable information for long-term planning and strategy formulation for enterprises to better adapt to the dynamic changes in the market and environment. The above three aspects jointly show the outstanding contribution of differential game model in the research of internal carbon pricing, and provide strong theoretical support and practical guidance for enterprises. This paper investigates the impact of three dynamic strategies for internal carbon pricing on enterprises' carbon emission reduction and goodwill. The study focuses on the interaction between the controlling party, represented by the enterprises, and the controlled party, represented by internal organizations, by constructing a differential game model. The following conclusions are drawn from the analysis:

(1) Under certain conditions, the carbon emission reduction and goodwill of enterprises under the three strategies gradually increase over time and reach a stable level. In the evolutionary process, the carbon emission reduction and goodwill values of enterprises under Model S (implementing internal carbon pricing without secondary investment and with shared emission reduction costs) are consistently higher than those under Model N ((implementing internal carbon pricing without secondary investment and shared emission reduction costs). When the internal organization's profit distribution ratio π_D is high and the internal carbon pricing coefficient ϕ is low, Model C (implementing internal carbon pricing with secondary investment) is the optimal choice for enterprises. This indicates that when utilizing internal carbon pricing as a carbon management tool, enterprises should not overlook the importance of fostering cooperation within internal organizations. Merely imposing a high internal carbon fee without providing sufficient incentives to internal organizations may have short-term effects on carbon emission reduction and goodwill accumulation. However, it may not align with the long-term objectives of sustainable production activities for enterprises.

(2) According to the analysis of the variations in the discount rate ρ and the internal carbon fee collection ratio ϕ on the total system profit, carbon emission reduction, and internal carbon price, the following observations can be made: When enterprises exhibit short-sighted behavior, they tend to prioritize maximizing short-term profits, resulting in reduced utilization of internal carbon pricing. Under the influence of short-sighted behavior, the internal carbon price for the complete collection of internal carbon fees (Models N and S) remains higher than the internal carbon price for incomplete fee collection (Model C) but eventually converges to a stable value. As for the increase in the internal carbon fee collection ratio ϕ, it leads to a decrease in carbon emission reduction, enterprises' goodwill, and internal carbon price under Model C. This indicates that when implementing internal carbon pricing strategies, enterprises should consider the potential short-sighted behavior arising from expected changes in technology, prices, and demand patterns associated with climate change-related events. Enterprises can set different internal carbon prices based on anticipated psychological values to address the uncertainties brought about by these changes.

This study has designed and supplemented the implementation strategies for internal carbon pricing and further validated the impact of internal carbon pricing on enterprises' carbon reduction and goodwill (Zhang, Lou, 2018). This provides recommendations for enterprises in dealing with uncertain carbon risks in the future and offers new insights into carbon pricing and enterprises' carbon regulation. The management implications are as follows: when applying internal carbon pricing, enterprises should focus on setting clear carbon emission reduction targets, taking into account changes in internal and external environments, motivating collaboration among internal organizations, and ensuring that internal pricing is consistent with corporate strategy. First, transparency and communication are key. Enterprises need to ensure that employees understand the purpose and mechanism of carbon pricing, and build employee identity with carbon reduction targets. Second, enterprises should continuously monitor and evaluate the effect of carbon emission reduction in combination with the carbon market mechanism to lay a foundation for timely adjustment of strategies. In addition, companies can improve employee awareness of carbon emission reduction through education and training, and incorporate internal carbon pricing into corporate social responsibility to demonstrate a sense of environmental responsibility and enhance corporate image. Ultimately, ensuring compliance and policy alignment of carbon pricing strategies will help companies better address climate change challenges and achieve sustainable business goals.

However, this paper has limitations in that it only examines the implementation strategies of internal carbon fees among the three internal carbon pricing methods, without considering shadow pricing and implicit pricing. These areas represent future research priorities.

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

LY: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft. ZH: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. BE: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. LL: Conceptualization, Formal Analysis, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing.

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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.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenrg.2023.1304272/full#supplementary-material

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