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Biform Differential Game Approach to Dynamic Carbon Reduction Cooperation in Transnational Supply Chains under CBAM

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Abstract: The Carbon Border Adjustment Mechanism (CBAM) is a border tax implemented by highly carbon-regulation countries (HCRC) on imports from less carbon-regulation countries (LCRC). To analyze carbon reduction cooperation in transnational supply chains under CBAM, this study develops a biform differential game model involving a distributor in HCRC and two manufacturers (from HCRC and LCRC) supplying homogeneous products through the distributor to the HCRC market. Within this framework, supply chain members cooperate in carbon reduction while independently setting the wholesale prices or retail prices. The findings reveal a key distinction between cooperative and non-cooperative modes: under non-cooperation, pricing and emission reduction decisions remain static, whereas under cooperation, they dynamically evolve and gradually stabilize, demonstrating the cooperation model's adaptability to long-term coordination. Moreover, as the CBAM price increases, distributors in the cooperative model increase the LCRC product sales but reduce them in the non-cooperative setting. Consequently, under cooperation, the distributor's profit increases with CBAM prices, while under non-cooperation, the profit follows an inverse U-shaped pattern. Finally, the cooperative mechanism enhances sales, emission reductions, and both LCRC and HCRC manufacturers' profits compared to the non-cooperative model. However, the distributor achieves

higher profits only when CBAM prices are sufficiently high. Therefore, it is advisable for the distributor to adopt the cooperative strategy conditionally, pursuing it primarily when CBAM prices are high to ensure that profit incentives remain aligned with carbon reduction objectives.

Keywords: Supply chain; Carbon Border Adjustment Mechanism; Biform differential game; Carbon reduction

1. Introduction

Carbon Border Adjustment Mechanism (CBAM) is a policy implemented by the European Union (EU) to mitigate carbon leakage in non-EU nations (Chang, Lu, and Tang 2026; Jia, Hu, and Chen 2025). The primary cause of carbon leakage is the stricter carbon regulations enforced by the EU, hereafter referred to as highly carbon-regulation countries (HCRC). When a manufacturer located in less carbon-regulation countries (LCRC) exports products to the HCRC market, HCRC manufacturers face a cost disadvantage due to their higher carbon costs, which diminishes their competitiveness against LCRC products. CBAM levies a carbon tax on LCRC products based on the carbon tax disparity between LCRC and HCRC (hereinafter referred to as the CBAM price), ensuring that LCRC products incur the same carbon costs as those from HCRC (Zhou et al., 2024). Therefore, both LCRC and HCRC manufacturers face substantial carbon cost pressures under CBAM, which negatively impact their profitability and global competitiveness.

Carbon reduction investments have become a critical strategy for transnational supply chains to mitigate CBAM exposure, because they directly lower embedded emissions and thus the importer's CBAM liability. Prior research and practice highlight three features of carbon reduction investments. First, carbon reduction investments typically require substantial upfront investments in process technologies. For example, GravitHy has raised €60 million to construct a hydrogen direct-reduction facility that could cut CO_2 emissions by up to 90%[1]. Second, carbon reduction investments are long-horizon dynamic process since carbon reduction equipment behaves like a depreciating capital stock with performance decay. Without continued investment in low-carbon technologies and equipment, aging and depreciation naturally erode carbon reductions (Jiang, Xu, and Zhang 2025; Xie, Fang, and Li 2024; Wang, Xu, and Zhu 2021). For example, in amine-based carbon capture, solvents such as MEA oxidize, thermally degrade, and can be lost as aerosols. Without active management, capture efficiency declines[2]. Finally, carbon reduction investments create greener product attributes, which attract environmentally conscious consumers with a clear willingness to pay a premium (Yu, Yang, and Zhang

[1] https://innoenergy.com/news-resources/gravithy-announces-a-60-million-fundraising/

[2] https://publications.ieaghg.org/technicalreports/2022-03%20Prime%20Solvent%20candidates%20for%20next%20generation%20of%20PCC%20plants.pdf?utm

2025), thus providing a direct incentive for firms to undertake such investments (Wang, Xu, and Zhu 2021; Zhu et al. 2025).

Because carbon reduction investments are highly capital intensive, distributors and downstream importers increasingly engage in upstream decarbonization. Under CBAM, it is the distributor (or importer) that directly bears the border carbon charge, which depends on the embedded emissions of imported products. As a result, reducing emissions at the production stage becomes a critical lever for distributors to control long-term carbon costs. For example, Marcegaglia, a leading European steel processor and distributor, has joined the investor group of GravitHy and has also invested in H2 Green Steel, alongside signing long-term offtake agreements for low-carbon steel[3]. These investments allow Marcegaglia to secure stable access to low-emission inputs and to mitigate future CBAM liabilities at their source. Similarly, the BMW Group, as a major downstream buyer and importer of steel-intensive products, has invested in CO_2-free steelmaking technology developed by the American startup Boston Metal to reduce embedded emissions in its supply chain[4]. By sharing abatement costs upstream, distributors can directly lower embedded emissions, reduce CBAM payments, and stabilize long-term supply relationships. Moreover, carbon reduction efforts enhance products' green attributes, which are increasingly valued by consumers and can stimulate demand (Zhu et al. 2025). These effects make cooperation an important strategy for easing CBAM cost pressures in the steel industry, while also improving the competitiveness of low-carbon products in the market.

Although carbon reduction cooperation is important, the inevitable pricing negotiations among supply chain members complicate the cooperation mechanisms. In other words, cooperation and non-cooperation often coexist simultaneously in transnational supply chains. From a cooperation perspective, when HCRC distributors are willing to invest in carbon reduction with HCRC and LCRC manufacturers, they need to develop cooperative strategies that include determining appropriate carbon reduction investment ratios between the manufacturers and establishing suitable carbon reduction efforts. From a competition perspective, due to the homogeneous nature of the products offered by LCRC and HCRC manufacturers, a competitive relationship exists between them. Consequently, HCRC distributors need to develop distinct pricing strategies for each type of product, while both LCRC and HCRC manufacturers must establish appropriate wholesale pricing strategies to maximize their respective profits. Therefore, there is an interdependent relationship between cooperation strategies and competition strategies, which complicates the design of supply chain cooperation mechanisms.

To analyze the carbon reduction cooperation mechanisms, we propose a novel biform differential game. The biform game integrates non-cooperative and cooperative game approaches into a unified framework (Brandenburger and Stuart 2007; Jia et al. 2023; Zheng et al. 2024), making it particularly

[3] https://www.prnewswire.com/news-releases/h2-green-steel-in-1-79-billion-green-steel-deal-with-marcegaglia-301812829.html

[4] https://www.press.bmwgroup.com/global/article/detail/T0405678EN

suitable for analyzing the coexistence of cooperation and non-cooperation in transnational supply chain. At the same time, the strategic environment under CBAM evolves dynamically. As the carbon reduction amounts depreciate over time, the effective emission levels change accordingly, which alters the associated CBAM costs. These temporal changes require manufacturers and the distributor to continuously adjust their carbon reduction efforts, wholesale prices, and retail prices in response to the evolving carbon cost pressures. As a result, the decisions for cooperation and non-cooperation co-evolve with the emission trajectory, giving rise to path-dependent strategic adjustments that cannot be captured by a static model. We employ a differential game to characterize the long-term carbon reduction investment strategies and to reflect how supply chain members adjust their decisions over time under CBAM.

Therefore, this study examines a transnational supply chain consisting of one HCRC distributor and two manufacturers (one in HCRC and one in LCRC) under the context of LCRC implementing carbon tax policies and HCRC enforcing carbon tax and CBAM. By combining the biform game and differential game frameworks, we present a novel biform differential game to investigate the following questions:

RQ1: What are the impacts of the CBAM price on the decisions and profits of the distributor and manufacturers, as well as on environmental outcomes, in both non-cooperative game and biform differential game models?

RQ2: How does the cooperation mechanism based on biform differential games alter the decisions of distributors and manufacturers compared to the non-cooperative game?

RQ3: Is the cooperation mechanism based on the biform differential game always beneficial for distributors, manufacturers, and the environment?

The remainder of this paper is organized as follows. Section 2 reviews the relevant literature. Section 3 presents the model formulation. The basic model, which does not incorporate the biform game mechanism (referred to as Model N), is introduced in Section 4. Section 5 provides a detailed presentation of the biform differential game model (referred to as Model B) within the context of a cooperative transnational supply chain that includes carbon reduction investment incentives for distributors. Section 6 conducts equilibrium analyses and numerical studies, comparing the outcomes under Models N and B. Finally, Section 7 concludes the study.

2. Literature review

The literature review is structured around two core themes that underpin this study: the Carbon Border Adjustment Mechanism (CBAM), cooperation mechanisms for carbon reduction and biform game in the supply chain.

2.1. Carbon Border Adjustment Mechanism

The Carbon Border Adjustment Mechanism (CBAM) is a border tax proposed by the European Union. It primarily targets industries such as steel and cement, as these sectors contribute significantly to overall carbon emissions (Rihner et al. 2025). Current research on the CBAM primarily focuses on two aspects: one is the economic and environmental impact assessment of CBAM, and the other is strategies for response (Li et al. 2023; Zhong and Pei 2024). In terms of economic and environmental impact assessment, studies indicate that CBAM may have disproportionate socio-economic impacts on EU trading partners, particularly developing countries and emerging economies (Böhringer et al. 2022; Magacho, Espagne, and Godin 2024; Zhong and Pei 2024), and it may not necessarily lead to a reduction in global emissions (Fang et al., 2020; Zhou et al., 2024). For instance, Banerjee (2021) analyzed the combined effects of border carbon adjustments and domestic carbon adjustments on India's carbon reduction and macroeconomic outcomes. Sun et al. (2024) found through a Computable General Equilibrium model that CBAM has limited effects on reducing carbon leakage, while Huang, Tan, and Toktay (2021) argued that CBAM can effectively reduce carbon leakage.

Regarding response strategies, Lu et al. (2024) explored how Chinese home appliance companies can address CBAM through product development and circular design strategies. Zhou et al. (2024) examined LCRC's strategies for responding to CBAM from a transnational supply chain perspective, suggesting the allocation of carbon quotas to manufacturers or providing subsidies to reduce their emissions reduction costs. Chang, Lu, and Tang (2026) examined how LCRC should implement a carbon tax in response to CBAM, revealing a dynamic relationship between CBAM intensity and optimal carbon tax rates.

This study focuses on the carbon reduction cooperation mechanisms among supply chain members under CBAM, analyzing the decision-making behaviors of manufacturers and distributors and their environmental impacts. Unlike existing research that often analyzes the impacts of CBAM from a macroeconomic perspective, this study starts from the internal cooperation mechanisms of the supply chain, examining how distributors and manufacturers can collaborate to invest in carbon reduction technologies, and how this cooperation impacts their pricing strategies, sale quantities, and profits. Therefore, this study is more micro-oriented and offers greater feasibility and operational applicability.

2.2. Cooperation mechanisms for carbon reduction

Existing research on cooperation mechanisms has primarily focused on two areas: the content of cooperation and the methods used. The content of cooperation includes elements such as green technology licensing (Zhang, Zhu, and Lin 2024), carbon reduction (Dou and Choi 2024; Guo, Bai, and Lev 2025), and emission responsibilities (Gopalakrishnan et al. 2021). Cooperation methods mainly involve cost-sharing (Cheng et al. 2024; Jiang et al. 2025; Zhu, Xi, and Goh 2024) and joint investments (Qian et al. 2025). For instance, Ma et al. (2025) examine equity financing to support supplier carbon emission reduction and its impact on encroachment decisions, while Xia and Chen (2025) explore horizontal green R&D cooperation among manufacturers considering technological spillover effects. However, these studies have typically examined cooperation using static approaches. Some scholars have also explored dynamic cooperation. For instance, Yang and Zhang (2023) consider a carbon reduction alliance involving two participants and examine different income outcomes under the Nash bargaining solution and Shapley value allocation methods. He et al. (2023) analyzes bilateral participation contracts, investigating the dynamic cooperation strategies for carbon reduction among three participants.

Although this stream of research provides important theoretical foundations for cooperation mechanism design, it generally aims to align decentralized supply chain outcomes with those of a centralized system through coordination schemes under non-cooperative settings. In increasingly complex transnational supply chains, however, cooperation and non-cooperation often coexist. As illustrated by real-world cases discussed in the Introduction, such as Marcegaglia simultaneously investing in GravitHy and H2 Green Steel while sourcing steel from them, firms may engage in cooperative investment relationships while maintaining non-cooperative procurement relationships. To capture this realistic coexistence of cooperation and non-cooperation in transnational supply chains, this study adopts a dynamic biform game framework. Unlike prior studies that rely on contract coordination to replicate centralized decision-making outcomes, our approach models the coupling of non-cooperation and cooperation and provides a cooperation mechanism suitable for transnational supply chains operating under such intertwined strategic interactions.

2.3. Biform game in the supply chain

The biform game, introduced by Brandenburger and Stuart (2007), combines non-cooperative and cooperative game theories by modeling strategic actions in the non-cooperative part and the competitive environment in the cooperative part (Chatain and Zemsky 2007; Bennett 2013; Gui et al. 2018). This framework has been widely applied in supply chain management (Feess and Thun 2014; Jia et al. 2023). For instance, Zhang et al. (2024) utilized a biform game model to investigate the competitive strategies and collaborative investment strategies of traditional and renewable energy manufacturers. Zheng et al. (2024) proposed a coordination mechanism based on biform games to facilitate cooperative investments among carbon complementary supply chain members.

Existing studies on biform games have made cooperation mechanisms more realistic by revealing how firms design cooperative mechanisms in the presence of non-cooperative relationships. However, the existing biform game literature has exclusively examined the coupling of cooperation and non-cooperation in static settings. In transnational supply chains, both cooperation and carbon reduction investments inherently involve long-term dynamics, making a dynamic perspective essential. Consequently, incorporating dynamic elements into the traditionally static biform game framework constitutes a key methodological challenge and represents an important advancement in biform game research. Building on existing research on manufacturers' carbon reduction investment strategies (Cai and Jiang 2023; Dye and Hsieh 2024; Zhang and Yu 2024), we develop a novel biform differential game framework. This model not only provides new insights into the behavioral evolution of supply chain members during long-term cooperation but also serves as a reference for designing long-term strategic cooperation mechanisms for carbon reduction investments in complex transnational supply chain environments.

2.4. Contributions

Table 1 summarizes the key differences between this study and the most related literature.

Table 1. Comparison with most related literature

Papers	CBAM	Analytical level	Cooperation	Number of players	Dynamic abatement stock	Game framework
Sun et al. (2024)	√	Macro	–	–	–	CGE - GTAP
Zhou et al. (2024)	√	Micro	×	2	×	Cournot game
Chang, Lu, and Tang (2026)	√	Micro	×	1	×	Game with constrain
Wang et al. (2021)	×	Micro	√	2	×	Stackelberg game
Guo, Bai, and Lev (2025)	×	Micro	√	2	×	Cournot game
Zheng et al. (2024)	×	Micro	√	3	×	Biform game
Yuan, Wang, and Li (2024)	×	Micro	×	2	√	Differential game
Jiang, Xu, and Zhang (2025)	×	Micro	×	2	√	Differential game
He et al. (2023)	×	Micro	√	3	√	Differential game
This study	√	Micro	√	3	√	Biform differential game

First, this study analyzes tri-party cooperation under CBAM with dynamic carbon reduction stocks, where two competing manufacturers (LCRC and HCRC) are connected through a single HCRC distributor. Prior research has either (i) examined CBAM at a macro level, (ii) simplified into two-party settings, or (iii) treated carbon reduction as static. By modeling simultaneous non-cooperation and cooperation under dynamic depreciation, the study provides a more realistic characterization of transnational supply chains confronting CBAM's long-run pressures.

Second, this study contributes to the literature on carbon reduction cooperation by modeling the coexistence of cooperation and non-cooperation in transnational supply chains. While existing cooperation mechanisms, both static and dynamic, primarily aim to coordinate decentralized decisions toward centralized outcomes, they typically ignore the fact that firms continue to make procurement and pricing decisions independently. By adopting a dynamic biform game framework, this study captures cooperative carbon reduction investment alongside non-cooperative procurement and pricing behavior, thereby providing a more realistic representation of strategic interactions in transnational supply chains operating under CBAM.

Third, this study makes a fundamental methodological contribution to the biform game literature by extending the traditionally static biform framework into a dynamic setting. Building on differential game models of carbon reduction investment, we develop a biform differential game with depreciating carbon reduction stocks, where coalition values are derived from HJB-based intertemporal value functions. Moreover, unlike existing differential game studies that assume exogenous cost-sharing parameters, our framework generates endogenous and state-dependent cost-sharing ratios through Shapley-based discounted values. Through the endogenous and bidirectional coupling of cooperative and non-cooperative components, this study establishes a dynamically coherent biform game structure that has not been achieved in prior biform or differential game research.

Collectively, these contributions establish a methodological departure from existing differential game and biform game studies and offer a theoretically grounded and practically relevant framework for understanding long-term carbon reduction cooperation in transnational supply chains under CBAM.

3. Model construction

This section considers a supply chain comprising two manufacturers (M_L in HCRC and M_H in LCRC) and a HCRC distributor. Manufacturers M_L and M_H wholesale their products to the distributor R, located in HCRC, at wholesale prices $w_L(t)$ and $w_H(t)$, respectively. The distributor then sells the products in the HCRC market at retail prices $p_L(t)$ and $p_H(t)$, and there exists a competitive relationship between the two products. The structure of the supply chain is illustrated in Fig. 1.

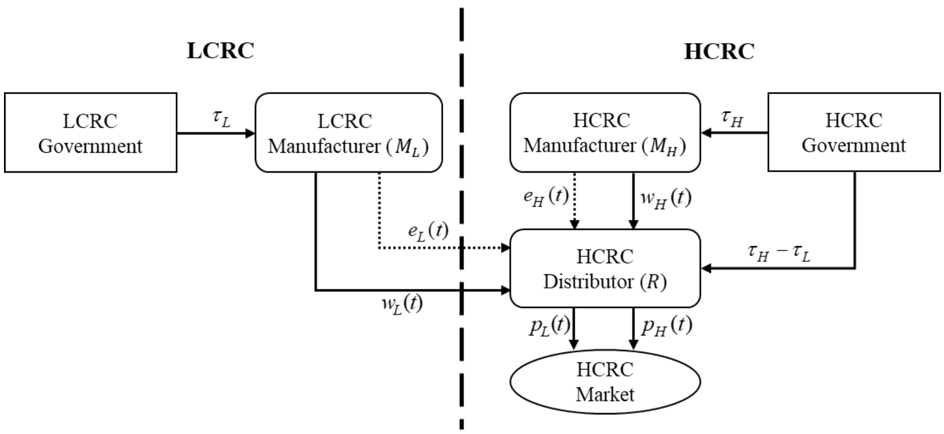


Fig. 1 The structure of the supply chain

To promote low-carbon sustainable development, both countries have implemented carbon taxes (τ_L and τ_H) to incentivize manufacturers to invest in emissions reduction technologies. Notably, the carbon tax rate in LCRC is lower than that in HCRC, i.e., $\tau_L < \tau_H$. Consequently, the HCRC government imposes a border tax $\tau_H - \tau_L$ on imported products from manufacturer M_L to ensure that both manufacturers (M_L and M_H) bear the same carbon cost. For example, the EU's CBAM requires importers to bear the related carbon costs based on the carbon tax differential between the EU and the country of product origin. Under the incentives provided by carbon taxes and CBAM, both manufacturers invest in carbon reduction technologies to lower their carbon emission costs.

Given that manufacturers' carbon reduction efforts evolve dynamically over time, this study adopts a differential game framework to characterize their long-term abatement investment decisions. Although the distributor co-invests in emission reduction with the manufacturers, the competitive relationship arises between the two manufacturers, who compete through the distributor's bilateral pricing decisions. To capture the cooperation in carbon reduction investment and non-cooperation in pricing, we introduce a novel biform differential game mechanism that integrates cooperative and non-cooperative components within a unified framework. This approach enables us to model how cost-sharing incentives interact with competitive pricing decisions over time. We now outline the key features of this game structure.

Production costs: This study considers LCRCs such as China and India, where labor and resource costs are relatively lower compared to HCRCs like the European Union. To distinguish the differences in production costs between the two manufacturers, we assume that the production cost for M_H is c, while the production cost for M_L is 0. This assumption simplifies the model and does not affect the main conclusions of the paper.

Carbon reduction costs: As noted in the Introduction, carbon reduction investments typically require substantial upfront investments in process technologies. Consistent with the literature (Chen et al. 2025; Jiang et al. 2025; Zheng et al. 2025), we model the investment cost of manufacturers M_L and M_H at time t with a convex quadratic function, specifically $ke_L^2(t)/2$ and $ke_H^2(t)/2$. Here, $e_L(t)$ and $e_H(t)$ denote the ongoing carbon reduction efforts of M_L and M_H, which include routine operations and maintenance required. The k is a common investment cost parameter, reflecting sector-wide factor prices for carbon reduction inputs. This assumption reflects the premise that while the two manufacturers may differ in their abatement efficiencies, the basic cost structure of their carbon reduction efforts remains comparable. The use of the same investment cost coefficient simplifies the model without affecting the underlying cooperative mechanism or the core conclusions of the study. We assume that k is sufficiently large, which is consistent with the substantial and long-term nature of carbon reduction investments documented in practice (Savaskan, Bhattacharya, and Van Wassenhove 2004). Because such costs are difficult for a single firm to bear over time, cooperation becomes a natural way to sustain continuous investment. A forward-looking distributor therefore proposes an incentive contract that shares $\alpha(t)$ and $\beta(t)$ of the carbon reduction costs undertaken by M_L and M_H, respectively. We interpret $\alpha(t)$ and $\beta(t)$ as per period cost sharing coefficients that allocate ongoing carbon reduction costs between channel partners. These shares are not a one-time collaborative capital investment. They specify a continuing cost sharing arrangement that operates over time.

Product demand function: In our model, manufacturers M_L and M_H sell the same product in the same market, so they compete directly. Carbon reduction investment gives the product greener attributes that consumers with low carbon preferences value. Recent research also indicates that complex environmental metrics often confuse consumers and reduce the effectiveness of sustainability information, whereas substantive and concrete environmental actions, such as carbon reduction investments, tend to elicit stronger consumer responses[5]. We reflect this in the demand function by allowing each manufacturer's carbon reduction effort, which represents the scale of its investment, to raise its own demand (Zheng and Li 2023; Niu, Zhang, and Zhang 2024; Liu, Yu, and Feng 2025). The demand functions for LCRC and HCRC products are $q_L(t) = 1 - b_1 p_L(t) + b_2 p_H(t) + g e_L(t)$ and $q_H(t) = 1 - b_1 p_H(t) + b_2 p_L(t) + g e_H(t)$, respectively. We normalize total market size to 1. The parameter $b_1 > 0$ measures own price sensitivity, referred to as the price sensitivity coefficient. The parameter $b_2 > 0$ measures cross price sensitivity, referred to as the cross-price sensitivity coefficient. Given that the effect of a competitor's price on demand is expected to be lower than that of its own price, we assume that the cross-price sensitivity coefficient is less than the price sensitivity coefficient, i.e., $b_2 < b_1$. The parameter $g > 0$ captures the positive effect of a manufacturer's carbon reduction effort on demand.

Dynamic carbon reduction amounts: Building on the Introduction, carbon reduction investments are dynamic and operate over a long horizon. The realized carbon reduction at time t is directly linked to each manufacturer's carbon reduction effort and to depreciation of installed equipment. Following Vogt-Schilb, Meunier, and Hallegatte (2018), we treat $E_L(t)$ and $E_H(t)$ as stock variables that accumulate with current effort and decay over time. Similar to Wang, Xu, and Zhu (2021) and Jiang, Xu, and Zhang (2025), the dynamic process of $E_L(t)$ and $E_H(t)$ can be described as follows:

$$\frac{dE_L(t)}{dt} = \delta_L e_L(t) - \epsilon E_L(t), E_L(0) = E_{L0} \quad (1)$$

$$\frac{dE_H(t)}{dt} = \delta_H e_H(t) - \epsilon E_H(t), E_H(0) = E_{H0} \quad (2)$$

Here, E_{L0} and E_{H0} denote the initial carbon reduction amounts of M_L and M_H. These values reflect differences in baseline emissions. The parameters δ_L and δ_H ($\delta_H, \delta_L > 0$) measure the effectiveness of the carbon reduction efforts of M_L and M_H. They capture firm-level technological and organizational differences. The parameter $\epsilon > 0$ indicates the decay coefficient of carbon reduction amounts due to factors such as equipment aging and depreciation. We assume ε is the same for both manufacturers. Any steady state satisfies $\frac{dE_i(t)}{dt} = 0$, hence $\delta_i e_i^* = \epsilon E_i^*$ for $i \in \{L, H\}$. In the long run, carbon reduction effort exactly offsets depreciation and the stock of reductions remains constant.

[5] https://www.oecd.org/en/publications/how-do-consumers-interact-with-environmental-sustainability-claims-on-food_0587c663-en.html

Carbon costs: Carbon costs comprise a carbon tax component and a CBAM component. First, let the carbon tax rates in the LCRC and HCRC be τ_L and τ_H. Following Vogt-Schilb, Meunier, and Hallegatte (2018), baseline emissions per unit are treated as constant. Since initial carbon reduction amounts reflect differences in baseline emissions, we assume the per unit baseline for both $M_L$and $M_H$is the same and normalize it to one (Wang, Xu, and Zhu 2021; Zhou et al. 2024). Hence total baseline emissions at time t equal output, and realized emissions for M_L and M_H are $q_L(t) - E_L(t)$ and $q_H(t) - E_H(t)$. The carbon tax costs at time t are $\tau_L(q_L(t) - E_L(t))$ and $\tau_H(q_H(t) - E_H(t))$. Under the CBAM, the distributor pays a border levy equal to the difference in carbon prices between the HCRC and the LCRC multiplied by the embedded emissions of the imported good. The CBAM cost for the distributor is therefore $(\tau_H - \tau_L)(q_L(t) - E_L(t))$. In the following sections, we will refer to $\tau_H - \tau_L$ as the CBAM price.

The parameters used in the model are summarized in Table 2.

Table 2. Parameters in the model

Notation	Implication
Decision variables	
$q_L(t),\ q_H(t)$	The sale quantities of M_L and M_H
$e_L(t),\ e_H(t)$	The carbon reduction efforts of M_L and M_H
$w_L(t),\ w_H(t)$	The wholesale prices for M_L and M_H
$p_L(t),\ p_H(t)$	The retail prices of LCRC and HCRC products
$\alpha(t),\ \beta(t)$	The proportion of the carbon reduction investment costs shared by distributor for M_L and M_H at time t
State variables	
$E_L(t),\ E_H(t)$	The carbon reduction amounts for M_L and M_H at time t, $E_L(0) = E_{L0}, E_H(0) = E_{H0}$
Parameters	
$b_1,\ b_2$	The price sensitivity coefficient and the cross-price sensitivity coefficient
$\tau_L,\ \tau_H$	The carbon tax rates for LCRC and HCRC manufacturers
g	Coefficient reflects the effect of carbon reduction efforts on demand
k	Cost coefficient for emissions reduction
c	The production cost of HCRC manufacturers
r	Discount rate
ϵ	The decay coefficient of carbon reduction amounts
$E_{L0},\ E_{H0}$	The initial carbon reduction amounts for M_L and M_H
$\delta_H,\ \delta_L$	The coefficient reflecting the effect of the carbon reduction efforts of M_L and M_H on their respective carbon reduction amounts
$M_L,\ M_H,\ R$	Manufacturers of LCRC and HCRC, distributor
$\pi_L,\ \pi_H,\ \pi_R$	The profits of M_L, M_H and distributor

To compare the performance generated by the cooperation mechanism based on the biform differential game, we first constructed a non-cooperative differential game model (Model N) in Section 4, where the distributor does not provide investment incentives for carbon reduction technologies. Subsequently, in Section 5, we proposed an investment incentive mechanism based on the biform differential game to extend Model N, aimed at promoting an increase in carbon reduction efforts across the entire supply chain, referred to as Model B.

4. Equilibrium results

4.1. Non-cooperative differential game model (Model N)

In this non-cooperative game, M_L and M_H first determine their respective carbon reduction efforts $e_L(t)$ and $e_H(t)$, as well as their wholesale prices $w_L(t)$ and $w_H(t)$, based on the carbon tax policies of their respective countries. Subsequently, the distributor decides the retail prices $p_L(t)$ and $p_H(t)$ for the products of M_L and M_H. In this context, the profit functions for the distributor, M_L and M_H are defined as follows:

$$\pi_R^N = [p_L(t) - w_L(t)]q_L(t) + [p_H(t) - w_H(t)]q_H(t) - (\tau_H - \tau_L)[q_L(t) - E_L(t)] \quad (3)$$

$$\pi_L^N = w_L(t)q_L(t) - \tau_L[q_L(t) - E_L(t)] - ke_L^2(t)/2 \quad (4)$$

$$\pi_H^N = [w_H(t) - c]q_H(t) - \tau_H[q_H(t) - E_H(t)] - ke_H^2(t)/2 \quad (5)$$

Using backward induction, we first determine the retail prices set by the distributor as follows:

$$p_L^N(w_L, w_H, e_L, e_H) = \frac{b_1(1+ge_L)+b_2(1+ge_H)}{2(b_1^2-b_2^2)} + \frac{w_L+\tau_H-\tau_L}{2} \quad (6)$$

$$p_H^N(w_L, w_H, e_L, e_H) = \frac{b_1(1+ge_L)+b_2(1+ge_H)}{2(b_1^2-b_2^2)} + \frac{w_H}{2} \quad (7)$$

Next, M_L and M_H simultaneously determine their respective wholesale prices and carbon reduction efforts. By substituting Eqs. (6) and (7) into Eqs. (4) and (5), the objective functions for M_L and M_H are $\max_{w_L, e_L} \int_0^\infty \pi_L^N e^{-rt} dt$ and $\max_{w_H, e_H} \int_0^\infty \pi_H^N e^{-rt} dt$.

To obtain the Markov Perfect Equilibrium of the non-cooperative game, it is assumed that M_L and M_H have continuously bounded differential revenue functions $V_L^N(E_L, E_H)$ and $V_H^N(E_L, E_H)$ that satisfy the Hamilton-Jacobi-Bellman (HJB) equation for any variables $E_L, E_H \geq 0$, namely:

$$rV_L^N(E_L, E_H) = \max_{w_L, e_L} \left\{ \pi_L^N + \frac{\partial V_L^N}{\partial E_L}(\delta_L e_L - \epsilon E_L) + \frac{\partial V_L^N}{\partial E_H}(\delta_H e_H - \epsilon E_H) \right\} \quad (8)$$

$$rV_H^N(E_L, E_H) = \max_{w_H, e_H} \left\{ \pi_H^N + \frac{\partial V_H^N}{\partial E_L}(\delta_L e_L - \epsilon E_L) + \frac{\partial V_H^N}{\partial E_H}(\delta_H e_H - \epsilon E_H) \right\} \quad (9)$$

By solving the HJB equation, we obtain the equilibrium results for the distributor, M_L and M_H, as presented in Lemma 1. The proof can be found in Appendix A.

Lemma 1. In the model N, the feedback Nash equilibrium strategies are, respectively, expressed as:

$$w_L^{N*} = \frac{\begin{array}{c} 4k^2(r+\epsilon)[b_1(2+b_2(c+\tau_H)) - 2b_1^2(\tau_H - 2\tau_L) + b_2(1+b_2\tau_H - b_2\tau_L)] + g^4(r+\epsilon)\tau_L + \\ 4gk(b_2\delta_H\tau_H + 2b_1\delta_L\tau_L) - 2g^3\delta_L\tau_L - 2g^2k(r+\epsilon)(1 - b_1\tau_H + b_2(c+\tau_H) + 4b_1\tau_L) \end{array}}{[(4kb_1 - g^2)^2 - 4k^2b_2^2](r+\epsilon)}$$

$$e_L^{N*} = \frac{\begin{array}{c} 4(4b_1^2 - b_2^2)k\delta_L\tau_L - 2gk(r+\epsilon)[2b_1^2\tau_H - b_2 - b_2^2\tau_H - b_1(2+b_2(c+\tau_H))] \\ +2g^2(b_2\delta_H\tau_H - 2b_1\delta_L\tau_L) - g^3(r+\epsilon)(1 - b_1\tau_H + b_2(c+\tau_H)) \end{array}}{[(4kb_1 - g^2)^2 - 4k^2b_2^2](r+\epsilon)}$$

$$p_L^{N*}=\frac{b_1\left(1+ge_L^{N*}\right)+b_2\left(1+ge_H^{N*}\right)}{2\left(b_1^2-b_2^2\right)}+\frac{w_L^{N*}+\tau_H-\tau_L}{2}$$

$$w_H^{N*}=\frac{\begin{array}{c}4(2b_1+b_2)k^2(r+\epsilon)(1+b_1\tau_H)-2g^3\delta_H\tau_H-2g^2k(r+\epsilon)(1+3b_1\tau_H+b_2\tau_H)\\ c\left(g^2-4b_1k\right)\left(g^2-2b_1k\right)(r+\epsilon)+g^4(r+\epsilon)\tau_H+4gk(2b_1\delta_H\tau_H+b_2\delta_L\tau_L)\end{array}}{\left[(4kb_1-g^2)^2-4k^2b_2^2\right](r+\epsilon)}$$

$$e_H^{N*}=\frac{\begin{array}{c}4\left(4b_1^2-b_2^2\right)k\delta_H\tau_H-g^3(r+\epsilon)\left(1+b_2\tau_H-b_1(c+\tau_H)\right)+2g^2(b_2\delta_L\tau_L-2b_1\delta_H\tau_H)-\\ 2gk(r+\epsilon)\left[2b_1^2(c+\tau_H)-b_1(2+b_2\tau_H)-b_2\left(1+b_2(c+\tau_H)\right)\right]\end{array}}{\left[(4kb_1-g^2)^2-4k^2b_2^2\right](r+\epsilon)}$$

$$p_H^{N*}=\frac{b_1\left(1+ge_L^{N*}\right)+b_2\left(1+ge_H^{N*}\right)}{2\left(b_1^2-b_2^2\right)}+\frac{w_H^{N*}}{2}$$

Based on the equilibrium results from Lemma 1 and the dynamic equations (1) and (2), we can derive the expressions for the carbon reduction amounts of M_L and M_H at time t as follows:

$$E_L^{N*}=\frac{e^{-t\epsilon}\left[\begin{array}{c}E_{L0}g^4\epsilon(r+\epsilon)+2\left(1-e^{t\epsilon}\right)gk\delta_L(r+\epsilon)\left(\left(2b_1^2-b_2^2\right)\tau_H-b_2-b_1\left(2+b_2(c+\tau_H)\right)\right)\\ \left(1-e^{t\epsilon}\right)g^3\delta_L(r+\epsilon)\left(1-b_1\tau_H+b_2(c+\tau_H)\right)+4\left(4b_1^2-b_2^2\right)k\left(E_{L0}k\epsilon(r+\epsilon)-\left(1-e^{t\epsilon}\right)\delta_L^2\tau_L\right)-\\ 2g^2\left(b_2\left(1-e^{t\epsilon}\right)\delta_H\delta_L\tau_H-2b_1\left(2E_{L0}k\epsilon(r+\epsilon)-\left(1-e^{t\epsilon}\right)\delta_L^2\tau_L\right)\right)\end{array}\right]}{\left[(4kb_1-g^2)^2-4k^2b_2^2\right](r+\epsilon)\epsilon}$$

$$E_H^{N*}=\frac{e^{-t\epsilon}\left[\begin{array}{c}E_{H0}g^4\epsilon(r+\epsilon)-2g^2\left(4b_1E_{H0}k\epsilon(r+\epsilon)-2b_1\left(1-e^{t\epsilon}\right)\delta_H^2\tau_H-b_2\left(-1+e^{t\epsilon}\right)\delta_H\delta_L\tau_L\right)+\\ 2\left(1-e^{t\epsilon}\right)gk\delta_H(r+\epsilon)\left(\left(2b_1^2-b_2^2\right)(c+\tau_H)-b_1(2+b_2\tau_H)-b_2\right)+\\ 4\left(4b_1^2-b_2^2\right)k\left(E_{H0}k\epsilon(r+\epsilon)-\left(1-e^{t\epsilon}\right)\delta_H^2\tau_H\right)+\left(1-e^{t\epsilon}\right)g^3\delta_H(r+\epsilon)\left(1+b_2\tau_H-b_1(c+\tau_H)\right)\end{array}\right]}{\left[(4kb_1-g^2)^2-4k^2b_2^2\right](r+\epsilon)\epsilon}$$

4.2. Biform differential game model (Model B)

In this section, we extend the Model N by developing an investment incentive mechanism based on biform differential games to enhance carbon reduction efforts, referred to as the Model B. Revisiting the assumptions outlined in Section 3, in model B, the distributor proposes an investment incentive contract at time t and is willing to cover the initial carbon reduction technology investment costs for M_L and M_H, with respective contributions of $\alpha(t)$ and $\beta(t)$. Given such a contract, we establish a novel cooperation mechanism based on biform differential games, which combines elements of both non-cooperative and cooperative games to facilitate investment incentives.

In this section, we evaluate the cooperative surplus and its allocation, without yet assuming that all players agree to cooperate. This step characterizes the cooperative benchmark, and participation will later be determined by comparing cooperative and non-cooperative payoffs in Section 5.2. The biform differential game model consists of two distinct components in each time period: the non-cooperative part and the cooperative part.

The non-cooperative part: In this part, the distributor and the two manufacturers determine their non-cooperative pricing strategies at time t, denoted as $\left(w_L(t),w_H(t),p_L(t),p_H(t)\right)$. Specifically, M_L and M_H first establish their wholesale pricing strategies $w_L(t)$ and $w_H(t)$ through Nash equilibrium, after which the distributor sets the retail prices $p_L(t)$ and $p_H(t)$ for the products of M_L and M_H, respectively. Unlike the non-cooperative differential game described in Section 3, here the distributor and the two manufacturers initially engage in a cooperative game based on the investment incentive contract to forecast how the profits will be allocated at time t. Subsequently, they make non-cooperative pricing decisions based on the anticipated profit allocation. However, each combination of strategies chosen by the distributor and the two manufacturers creates a distinct competitive environment at time t, thereby influencing the cooperative dynamics of the cooperative game.

The cooperative part:

In this part, the distributor proposes an investment incentive contract at time $t$to stimulate the carbon reduction efforts of the two manufacturers. This leads to a three-player cooperative game in which the cooperative profits must be allocated among $\{M_L, M_H, R\}$. To derive this allocation, we first compute the characteristic values of all possible coalitions $S \subseteq N = \{\emptyset, L, H, R, LH, LR, HR, LHR\}$. The characteristic value of coalition S at time t, denoted as $v(w_L(t), w_H(t), p_L(t), p_H(t))(S)$, is abbreviated as $v_t(S)$ for simplicity. The empty coalition naturally yields zero profit, so $v_t(\emptyset) = 0$. For any given pricing strategy profile $(w_L(t), w_H(t), p_L(t), p_H(t))$, the value $v_t(S)$ depends on the coalition members' carbon reduction efforts $(e_L(t), e_H(t))$ and the corresponding cost-sharing ratios $\alpha(t)$ and $\beta(t)$. These effort decisions are derived by solving the HJB equation associated with coalition S. Based on the resulting characteristic function, the Shapley value is applied to allocate cooperative profits across the three players. This Shapley-based allocation is evaluated under the competitive pricing environment given by the non-cooperative part, and the resulting values serve as the objective functions for the distributor and the manufacturers in the subsequent Stackelberg pricing game.

Before solving the biform differential game, we clarify the solution structure, as illustrated in Fig. 2. In the cooperative part, we treat the pricing strategy profile $\left(w_L(t), w_H(t), p_L(t), p_H(t)\right)$ as parametric functions, not fixed numbers. Under these parametric prices, each coalition solves its HJB problem to obtain the optimal carbon reduction efforts $\left(e_L(t), e_H(t)\right)$ and the induced emission paths $\left(E_L(t), E_H(t)\right)$. Substituting these paths into the payoff integrals yields characteristic functions $v_t(S)$ that depend on the pricing parameters. The Shapley allocations $\varphi_L(v_t)$, $\varphi_H(v_t)$ and $\varphi_R(v_t)$ are then constructed from these parameter-dependent characteristic functions, so the cost-sharing ratios $\alpha(t)$ and $\beta(t)$ and their future trajectories are fully anticipated as functions of the emission states. These Shapley values are subsequently fed back into the non-cooperative game, where they define the effective profit functions of the manufacturers and the distributor.

In the non-cooperative stage, manufacturers and the distributor choose wholesale and retail prices in a Stackelberg game to maximize their profit. Because these values already incorporate the cooperative stage's optimal abatement decisions and emission trajectories, the resulting equilibrium pricing strategies and the induced emission paths are jointly determined and mutually consistent.

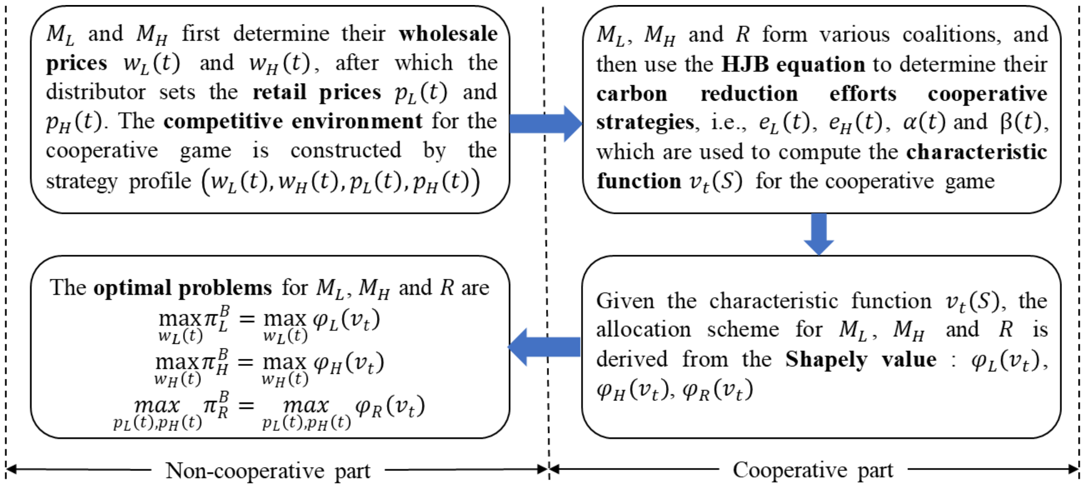


Fig. 2 Decision framework of Model B.

Based on this structure, we now start with the cooperative game part for the pricing strategy profile given.

(1) Cooperative game part:

In the cooperative game part, given the pricing strategies $(w_L(t), w_H(t), p_L(t), p_H(t))$, the characteristic value of each coalition at time t is its discounted payoff obtained from solving the corresponding HJB problem. This construction implies that the cooperative game evaluates payoffs over the entire future trajectory rather than at a single instant. Discounting is therefore naturally embedded in the characteristic function through the HJB formulation. As a result, the Shapley value is computed on integrated intertemporal value functions, not on instantaneous profit flows.

We utilize the Minimax or Maximin principle and HJB equation to compute the characteristic value $v_t(S)$ for any potential coalition S within the three-player cooperative game at time t. According to the Minimax or Maximin principle, coalition S seeks to determine its optimal decision to maximize its profits while its opposing coalitions aim to minimize those profits. For illustrative purposes, we consider the case of coalition $S = L$ and calculate its characteristic value $v_t(L)$. Since coalition L consists of a single participant, namely M_L, its opposing coalition consists of the remaining participants M_H and R. The profit function for M_L is $\pi_L^B = w_L(t)q_L(t) - \tau_L[q_L(t) - E_L(t)] - (1-\alpha(t))ke_L^2(t)/2$. For the given pricing strategies $(w_L(t), w_H(t), p_L(t), p_H(t))$, the characteristic value $v_t(L)$ can be calculated by applying the Maximin principle, resulting in the following optimization problem:

$$\begin{aligned} v_t(L) &= \max_{e_L} \min_{e_H,\alpha,\beta} \{\pi_L^B\} \\ &= \max_{e_L} \min_{e_H,\alpha,\beta} \{w_L(t)q_L(t) - \tau_L[q_L(t) - E_L(t)] - (1-\alpha(t))ke_L^2(t)/2\} \end{aligned} \tag{10}$$

According to the Maximin theorem, coalition L engages in a zero-sum game with its opposing coalition. Thus, we have $\max_{e_L} \min_{e_H,\alpha,\beta}\{\pi_L^B\} = \min_{e_H,\alpha,\beta} \max_{e_L}\{\pi_L^B\}$。To solve this problem, we assumed that coalition L has continuously bounded differential revenue functions $V_L^B(E_L, E_H)$ that satisfy the HJB equation for any variables $E_L, E_H \geq 0$, namely:

$$rV_L^B(E_L,E_H)=\max_{e_L}\min_{e_H,\alpha,\beta}\left\{\pi_L^B+\frac{\partial V_L^B}{\partial E_L}(\delta_L e_L-\epsilon E_L)+\frac{\partial V_L^B}{\partial E_H}(\delta_H e_H-\epsilon E_H)\right\} \tag{11}$$

By solving Eq. (11), we can obtain the characteristic value $v(L)$ for coalition L. Subsequently, we present the characteristic values for all coalitions in Lemma 2.

Lemma 2. Given the pricing strategies $(w_L(t), w_H(t), p_L(t), p_H(t))$, the characteristic values of all possible coalitions S $(S \neq \emptyset)$ at time t are given as follows:

$$v_t(L)=A(w_L-\tau_L)+e^{-t\epsilon}E_{L0}\tau_L+\frac{\left[\begin{array}{c}(g(r+\epsilon)(w_L-\tau_L)+\delta_L\tau_L)\\ \left(g\epsilon(r+\epsilon)(w_L-\tau_L)+\delta_L\tau_L\left(2r+\epsilon-2(r+\epsilon)e^{-t\epsilon}\right)\right)\end{array}\right]}{2k\epsilon(r+\epsilon)^2}$$

$$v_t(H)=B(w_H-\tau_H-c)+e^{-t\epsilon}E_{H0}\tau_H+\frac{\left[\begin{array}{c}(g(r+\epsilon)(w_H-\tau_H-c)+\delta_H\tau_H)\\ \left(g\epsilon(r+\epsilon)(w_H-\tau_H-c)+\delta_H\tau_H\left(2r+\epsilon-2(r+\epsilon)e^{-t\epsilon}\right)\right)\end{array}\right]}{2k\epsilon(r+\epsilon)^2}$$

$$v_t(R)=A(p_L-w_L-\tau_H+\tau_L)+B(p_H-w_H)+e^{-t\epsilon}E_{L0}(\tau_H-\tau_L)$$

$$v_t(LH)=A(w_L-\tau_L)+B(w_H-\tau_H-c)+e^{-t\epsilon}(E_{L0}\tau_L+E_{H0}\tau_H)+$$
$$\frac{\left[\begin{array}{c}(g(r+\epsilon)(w_L-\tau_L)+\delta_L\tau_L)\\ \left(g\epsilon(r+\epsilon)(w_L-\tau_L)+\delta_L\tau_L\left(2r+\epsilon-2(r+\epsilon)e^{-t\epsilon}\right)\right)\end{array}\right]+\left[\begin{array}{c}(g(r+\epsilon)(w_H-\tau_H-c)+\delta_H\tau_H)\\ \left(g\epsilon(r+\epsilon)(w_H-\tau_H-c)+\delta_H\tau_H\left(2r+\epsilon-2(r+\epsilon)e^{-t\epsilon}\right)\right)\end{array}\right]}{2k\epsilon(r+\epsilon)^2}$$

$$v_t(LR)=A(p_L-\tau_H)+B(p_H-w_H)+e^{-t\epsilon}E_{L0}\tau_L+\frac{\left[\begin{array}{c}(g(r+\epsilon)(p_L-\tau_H)+\delta_L\tau_H)\\ \left(g\epsilon(r+\epsilon)(p_L-\tau_H)+\delta_L\tau_H\left(2r+\epsilon-2(r+\epsilon)e^{-t\epsilon}\right)\right)\end{array}\right]}{2k\epsilon(r+\epsilon)^2}$$

$$v_t(HR)=A(p_L-w_L-\tau_H+\tau_L)+B(p_H-\tau_H-c)+e^{-t\epsilon}[(E_{L0}+E_{H0})\tau_H-E_{L0}\tau_L]+$$
$$\frac{\left[(g(r+\epsilon)(p_H-\tau_H-c)+\delta_H\tau_H)\left(g\epsilon(r+\epsilon)(p_H-\tau_H-c)+\delta_H\tau_H\left(2r+\epsilon-2(r+\epsilon)e^{-t\epsilon}\right)\right)\right]}{2k\epsilon(r+\epsilon)^2}$$

$$v_t(LHR)=A(p_L-\tau_H)+B(p_H-\tau_H-c)+e^{-t\epsilon}[(E_{L0}+E_{H0})\tau_H-E_{L0}\tau_L]+$$
$$\frac{\left[\begin{array}{c}(g(r+\epsilon)(p_L-\tau_H)+\delta_L\tau_H)\\ \left(g\epsilon(r+\epsilon)(p_L-\tau_H)+\delta_L\tau_H\left(2r+\epsilon-2(r+\epsilon)e^{-t\epsilon}\right)\right)\end{array}\right]+\left[\begin{array}{c}(g(r+\epsilon)(p_H-\tau_H-c)+\delta_H\tau_H)\\ \left(g\epsilon(r+\epsilon)(p_H-\tau_H-c)+\delta_H\tau_H\left(2r+\epsilon-2(r+\epsilon)e^{-t\epsilon}\right)\right)\end{array}\right]}{2k\epsilon(r+\epsilon)^2}$$

where $A=1+b_2p_H-b_1p_L$, $B=1-b_1p_H+b_2p_L$.

Lemma 2 provides the characteristic values for all possible coalitions. In cooperative game theory, the characteristic value represents the minimum payoff that a coalition can attain, reflecting its bargaining power in the cooperative game. It is essential that the total payoff received by any coalition member during the distribution process is no less than the characteristic value of that coalition. This principle ensures that the returns obtained through collaboration meet at least the minimum level defined by the coalition's bargaining power, thereby maintaining the rationality and effectiveness of cooperation. Subsequently, we plan to utilize the Shapley value to determine the allocation scheme.

Proposition 1. For any coalitions $S1 \subseteq N$ and $S2 \subseteq N$, the characteristic function satisfies $v_t(S1)+v_t(S2)\leq v_t(S1\cup S2)+v_t(S1\cap S2)$. The proof can be found in Appendix B.

Proposition 1 shows that the characteristic function of the cooperative game is convex and super-additive. These properties imply that a larger coalition always generates no less joint value than smaller coalitions, and that the contribution of each participant becomes greater when it joins a larger group. Therefore, the grand coalition LHR achieves the highest total surplus, and its core is non-empty. The

Shapley value, which is constructed from marginal contributions across all coalition structures, lies within this core and provides an allocation that is both individually rational and collectively efficient. It is worth noting that Proposition 1 may not hold when the CBAM price becomes excessively high, because an excessively high CBAM price could drive the unit profit of the LCRC manufacturer's exports into negative territory. Such scenarios fall outside the scope of our model, as they correspond to economically infeasible conditions under which the LCRC manufacturer would not participate in the market regardless of coalition structure. Therefore, within the economically meaningful parameter domain we consider, Proposition 1 ensures that the grand coalition remains the only stable coalition.

The Shapley value is a widely recognized mechanism for profit allocation, designed to allocate the total gains from a cooperative game fairly by evaluating each participant's marginal contribution across various coalition structures. The Shapley value for each member of the coalition can be calculated as follows:

$$\varphi_i(v) = \sum_{S \in N} \frac{(3-|S|)!\,(|S|-1)!}{3!}\left[v(S) - v(S \backslash i)\right], i \in \{L, H, R\} \tag{12}$$

where, $|S|$ represents the number of participants in coalition S, and $v(S \backslash i)$ denotes the characteristic value of the coalition formed by all members of S excluding participant i. Therefore, the Shapley values for the distributors and manufacturers M_L and M_H at time t can be summarized as Lemma 3 through Eq. (12).

Lemma 3. The Shapley values for the distributor and manufacturers are given as follows:

$$\begin{aligned}\varphi_R(v_t) = A(p_L - w_L - \tau_H + \tau_L) + B(p_H - w_H) - \frac{e^{-t\epsilon}\left[\delta_L^2(\tau_H^2 - \tau_L^2)\left(2(r+\epsilon) - (2r+\epsilon)e^{t\epsilon}\right)\right]}{4k\epsilon(r+\epsilon)^2} + \\ e^{-t\epsilon}E_{L0}(\tau_H - \tau_L) + \frac{\begin{bmatrix} g^2\epsilon((p_H-\tau_H)^2-(w_H-\tau_H)^2-(w_L-\tau_L)^2+(p_L-\tau_H)^2-2c(p_H-w_H))+ \\ 2g(1-e^{-t\epsilon})\left((p_H-w_H)\delta_H\tau_H+\delta_L\left((p_L-\tau_H)\tau_H-(w_L-\tau_L)\tau_L\right)\right)\end{bmatrix}}{4k\epsilon}\end{aligned} \tag{13}$$

$$\begin{aligned}\varphi_L(v_t) = A(w_L - \tau_L) + E_{L0}e^{-t\epsilon}\tau_L + \frac{e^{-t\epsilon}\left[\delta_L^2(\tau_H^2+\tau_L^2)(2(r+\epsilon)-(2r+\epsilon)e^{t\epsilon})\right]}{4k\epsilon(r+\epsilon)^2} \\ \frac{2\delta_L g((p_L-\tau_H)\tau_H+(w_L-\tau_L)\tau_L)(1-e^{-t\epsilon})+g^2\epsilon((p_L-\tau_H)^2+(w_L-\tau_L)^2)}{4k\epsilon}\end{aligned} \tag{14}$$

$$\begin{aligned}\varphi_H(v_t) = B(w_H - \tau_H - c) + E_{H0}e^{-t\epsilon}\tau_H + \frac{e^{-t\epsilon}\left[2\delta_H^2\tau_H^2(2(r+\epsilon)-(2r+\epsilon)e^{t\epsilon})\right]}{4k\epsilon(r+\epsilon)^2} \\ \frac{2\delta_H\tau_H g(p_H+w_H-2\tau_H-2c)(1-e^{-t\epsilon})+g^2\epsilon((p_H-\tau_H-c)^2+(w_H-\tau_H-c)^2)}{4k\epsilon}\end{aligned} \tag{15}$$

The convexity and super-additive of the cooperative game ensure that the aforementioned Shapley values satisfy both individual rationality and collective rationality. This implies that under the proposed allocation mechanism, all three participants are willing to engage in the grand coalition LHR. Subsequently, we will utilize the Shapley values of the three participants as their respective objective functions in a non-cooperative game framework to analyze their pricing decisions in a non-cooperative setting.

(2) Non-cooperative game part:

In the non-cooperative game part, the distributor and the two manufacturers engage in a Stackelberg pricing game, with their objective functions based on the revenue allocations predicted from the cooperative game. The optimal problems for the distributor, M_L and M_H in Model B are defined as follows:

$$\max_{p_L(t),p_H(t)} \pi_R^B = \max_{p_L(t),p_H(t)} \varphi_R(v_t) \tag{16}$$

$$\max_{w_L(t)} \pi_L^B = \max_{w_L(t)} \varphi_L(v_t) \tag{17}$$

$$\max_{w_H(t)} \pi_H^B = \max_{w_H(t)} \varphi_H(v_t) \tag{18}$$

Utilizing backward induction, we first determine the retail price decision of the distributor; subsequently, we solve for the wholesale price decisions of the two manufacturers, which are then substituted into the retail price to obtain the final equilibrium results. The optimal carbon reduction efforts under the biform differential game model corresponds to the optimal carbon reduction efforts of the grand coalition LHR, specifically: $e_L^{B*} = \frac{g(r+\epsilon)(p_L^{B*}-\tau_H)+\delta_L\tau_H}{k(r+\epsilon)}$, $e_H^{B*} = \frac{g(r+\epsilon)(p_H^{B*}-\tau_H-c)+\delta_H\tau_H}{k(r+\epsilon)}$. We can find that the carbon reduction efforts are directly influenced by retail prices and increase with them. Due to the complexity of the other outcomes, we present the results in Appendix C.

5. Analysis

5.1. The impact of the LCRC carbon tax rate

We analyze the impact of the LCRC carbon tax rate on the equilibrium results in the stable stage. Additionally, CBAM price is defined as the difference between the carbon tax rates of LCRC and HCRC, i.e., $\tau_H - \tau_L$. In our analysis, we consider the HCRC carbon tax rate as an exogenous variable. Therefore, the impact of the CBAM price on the equilibrium outcomes is exactly opposite to that of the LCRC carbon tax rate.

Proposition 2. (a) In Model N, $\frac{\partial q_{L\infty}^{N*}}{\partial \tau_L} > 0$, $\frac{\partial w_{L\infty}^{N*}}{\partial \tau_L} > 0$, $\frac{\partial e_{L\infty}^{N*}}{\partial \tau_L} > 0$, $\frac{\partial E_{L\infty}^{N*}}{\partial \tau_L} > 0$, $\frac{\partial p_{L\infty}^{N*}}{\partial \tau_L} > 0$.

(b) In Model B, $\frac{\partial q_{L\infty}^{B*}}{\partial \tau_L} < 0$, $\frac{\partial w_{L\infty}^{B*}}{\partial \tau_L} > 0$, $\frac{\partial e_{L\infty}^{B*}}{\partial \tau_L} > 0$, $\frac{\partial E_{L\infty}^{B*}}{\partial \tau_L} > 0$, $\frac{\partial p_{L\infty}^{B*}}{\partial \tau_L} > 0$.

Proposition 2(a) indicates that, in Model N, an increase in the LCRC carbon tax rate leads to higher sale quantities, wholesale prices, retail prices, carbon reduction efforts, and carbon reduction amounts for the LCRC manufacturer. This outcome can be understood through the following economic mechanism. When the government raises the LCRC carbon tax, manufacturer M_L immediately faces a higher emissions-related burden. To mitigate this cost pressure, manufacturer M_L increases its carbon reduction effort, which expands its steady-state carbon reduction amount and lowers its embedded emissions. As embedded emissions decline, the CBAM cost paid by the distributor also decreases, because CBAM charges are assessed based on the difference in carbon tax rates multiplied by embedded emissions. This CBAM pass-through effect reduces the delivered carbon cost of LCRC products, thereby stimulating demand. Although higher abatement raises the manufacturer's marginal cost and leads to a higher wholesale price, the reduction in CBAM costs more than offsets this effect, resulting in higher retail prices and higher sale quantities.

Proposition 2(b) shows that Model B differs from Model N in that the sales response reverses. Whereas the LCRC product's sale quantity increases with the carbon tax in Model N, it decreases in Model B. Under the cooperative mechanism, the distributor shares part of the carbon reduction investment cost, making the coalition's abatement incentives more sensitive to retail prices. When the LCRC carbon tax rises, the distributor increases retail prices more aggressively in order to induce higher abatement by the coalition and further reduce CBAM costs. This stronger price pass-through effect intensifies the retail price increase faced by consumers. As a result, even though abatement efforts and carbon reduction amounts continue to rise, the retail price increase dominates the CBAM-relief effect, leading to a decline in the steady-state sale quantity of LCRC products. Thus, in Model N, the CBAM-relief mechanism dominates and generates higher sales, whereas in Model B, the amplified price pass-through created by cost sharing reverses this effect and results in reduced sales.

Proposition 3. (a) In Model N, $\frac{\partial q_{H\infty}^{N*}}{\partial \tau_L} > 0$, $\frac{\partial w_{H\infty}^{N*}}{\partial \tau_L} > 0$, $\frac{\partial e_{H\infty}^{N*}}{\partial \tau_L} > 0$, $\frac{\partial E_{H\infty}^{N*}}{\partial \tau_L} > 0$, $\frac{\partial p_{H\infty}^{N*}}{\partial \tau_L} > 0$.

(b) In Model B, $\frac{\partial q_{H\infty}^{B*}}{\partial \tau_L} > 0$, $\frac{\partial w_{H\infty}^{B*}}{\partial \tau_L} > 0$, $\frac{\partial e_{H\infty}^{B*}}{\partial \tau_L} > 0$, $\frac{\partial E_{H\infty}^{B*}}{\partial \tau_L} > 0$, $\frac{\partial p_{H\infty}^{B*}}{\partial \tau_L} > 0$.

Proposition 3(a) demonstrates that, in Model N, an increase in the LCRC carbon tax rate also affects the decisions of the HCRC manufacturer, even though the tax is imposed only on manufacturer M_L. The economic logic is as follows. When the LCRC carbon tax rises, manufacturer M_L invests more in carbon reduction to reduce its tax burden, which in turn lowers the embedded emissions of LCRC products and reduces the distributor's CBAM payment. This improvement in the delivered carbon cost of LCRC products strengthens their market competitiveness, thereby exerting greater competitive pressure on manufacturer M_H. In response, manufacturer M_H increases its own carbon reduction effort to maintain competitiveness. Higher abatement reduces its domestic carbon tax cost and enhances the green attributes of its products, which attracts more consumers. Therefore, both the sale quantity and wholesale price of HCRC products rise as the LCRC carbon tax increases.

Proposition 3(b) shows that the impacts of the LCRC carbon tax rate on the decisions related to HCRC products in Model B remain the same as those in Model N. When the LCRC carbon tax increases, M_H continues to raise its abatement effort, carbon reduction amount, wholesale price, retail price and sale quantity. This outcome indicates that the cooperative mechanism does not change the underlying competitive-response pattern. M_H still reacts to the improved competitiveness of LCRC products by strengthening its own abatement and adjusting its pricing decisions. Therefore, the impacts in Model B remains identical to that in Model N.

Next, we employ numerical methods to illustrate the impact of the LCRC carbon tax rate on the sharing proportions and profits. The numerical simulation is based on parameter settings that reflect real-world data and prevailing policy environments. Although our analysis does not target a specific firm or industry, the simulation framework draws extensively on empirical statistics and international carbon-policy practices to ensure contextual relevance and practical realism. We also conduct sensitivity analyses on key parameters (ϵ, b_1, b_2, δ_H, δ_L, and g) to verify the robustness of our results. Since the findings are straightforward and these parameters are not central to the main theoretical insights, the full simulation outcomes are reported in the Appendix D.

The choice of numerical values primarily follows Jiang, Xu, and Zhang (2025) and Xie, Fang, and Li (2024). First, the discount rates and decay coefficient of carbon reduction amounts, r and ϵ, are set to 0.05 and 0.2, respectively, consistent with standard practices in dynamic environmental modeling, allowing the model to reflect the intertemporal nature of emissions and economic returns. The influence coefficient of the LCRC manufacturer's abatement effort is set to $\delta_L = 0.1$, with the initial carbon reduction amounts $E_{L0} = 0$. To capture technological heterogeneity between LCRC and HCRC manufacturers, the corresponding coefficient for the HCRC manufacturer is set to $\delta_H = 0.2$, and its initial carbon reduction amounts is $E_{H0} = 0.05$.

Demand parameters follow Zheng and Li (2023), with the price sensitivity coefficient $b_1 = 1$, the cross-price sensitivity coefficient $b_2 = 0.5$, and the influence coefficient of carbon reduction efforts on demand $g = 0.5$. The production cost of HCRC manufacturers is normalized to $c = 0.05$, based on Chang, Lu, and Tang (2026), who use $c = 50$ before normalization. Regarding carbon tax rate settings, the HCRC carbon tax is set at $\tau_H = 0.65$, consistent with the EU ETS average price of approximately 650 RMB per ton (Chang, Lu, and Tang 2026). Finally, we select a relatively large cost coefficient for emissions reduction, $k = 10$, to reflect the capital-intensive nature of carbon reduction investments. The time horizon is set to $t = 50$ to ensure convergence to the steady state.

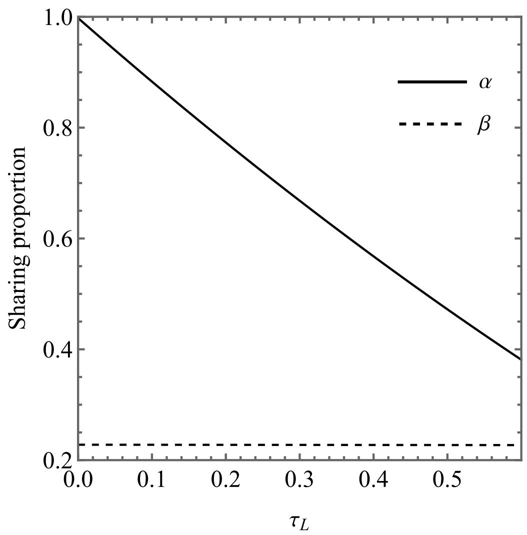
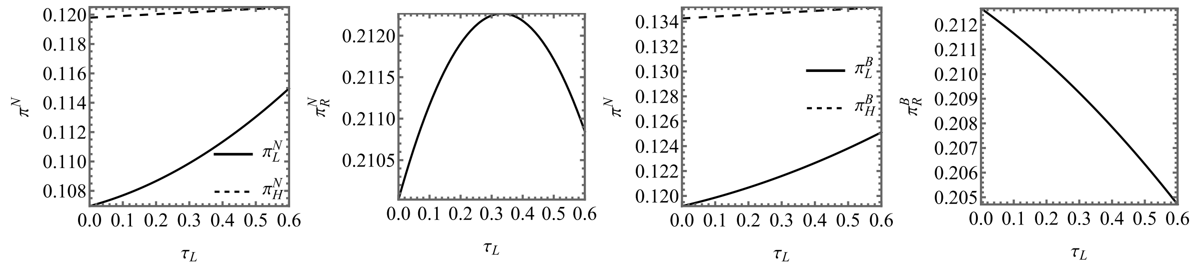


Fig. 3 The impact of the LCRC carbon tax rate on the sharing proportion

Fig. 3 illustrates that the proportion of carbon reduction investment costs shared between HCRC distributors and LCRC manufacturers is higher than that between HCRC distributors and HCRC manufacturers. Furthermore, the shared proportion decreases as the carbon tax rate in LCRC increases. This is because a lower carbon tax rate in LCRC reduces manufacturers' incentives to invest in emission reduction, which leads to higher CBAM costs borne by HCRC distributors. To mitigate these costs, distributors are likely to assume a larger share of the investment costs when the carbon tax rate in LCRC is low, thereby incentivizing LCRC manufacturers to invest in carbon reduction. This further indicates that higher CBAM prices strengthen HCRC distributors' incentive to engage in cooperation and share carbon reduction costs.



a b c d

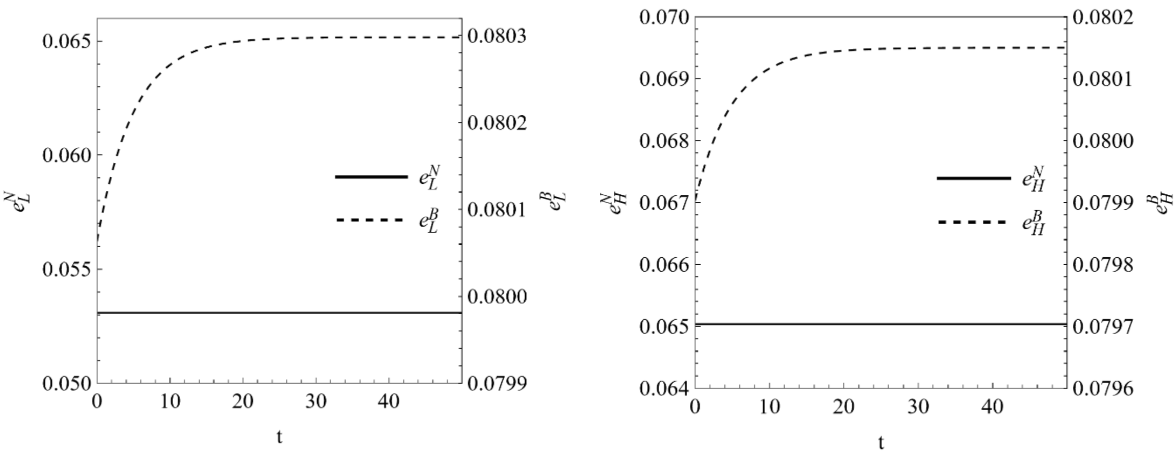
Fig. 4 The impact of the LCRC carbon tax rate on profits

Fig. 4a and 4b demonstrate that the profits of M_L and M_H both increase with the LCRC carbon tax rate, while the profits of the distributor first increase and then decrease as the tax rate rises in Model N. Firstly, the increase in the LCRC carbon tax rate elevates the carbon reduction efforts and carbon reduction amounts for M_H, which in turn boosts consumer demand and reduces carbon tax costs, leading to an increase in its profits. However, since the impact of the LCRC carbon tax rate on manufacturer M_H is less pronounced than that on M_L, the trend in profit growth for M_H is less noticeable. Secondly, M_L also experiences an increase in carbon reduction efforts and carbon reduction amounts in response to the rising LCRC carbon tax rate. Within the context of the CBAM, the combination of an increasing LCRC carbon tax rate and enhanced carbon reduction amounts for M_L significantly reduces the CBAM costs for the distributor. This situation enhances the bargaining power of M_L, allowing for an increase in the wholesale prices, which results in a profit increase that becomes more substantial with higher LCRC carbon tax rates. Finally, although the increase in the LCRC carbon tax rate leads to higher sale quantities for LCRC products, the rise in the wholesale prices for M_L surpasses the increase in retail prices for LCRC products (i.e. $\frac{\partial w_L^{N*}}{\partial \tau_L} > \frac{\partial p_L^{N*}}{\partial \tau_L}$, with proof provided in Appendix B). Consequently, this causes a reduction in the unit profit for the distributor. At lower LCRC carbon tax rates, the increase in sale quantities positively impacts the profits of the distributor; however, at higher tax rates, the decline in unit profits ultimately leads to a decrease in the profits of the distributor. In summary, an increase in the LCRC carbon tax rate enhances the profits of both M_L and M_H; however, a higher LCRC carbon tax rate negatively impact the profits of the distributor.

Fig. 4c and 4d illustrate that the profits of M_L and M_H both increase with the LCRC carbon tax rate, while the profits of the distributor decrease with this tax rate in Model B. For M_H, both the wholesale price and sale quantities of the product increase with the rising LCRC carbon tax rate, leading to an increase in profits. For M_L, carbon reduction cooperation amplifies the positive impact of the LCRC carbon tax rate on carbon reduction efforts. Since a higher LCRC carbon tax rate yields greater benefits in terms of carbon tax cost reduction, the increase in the LCRC carbon tax rate can enhance the carbon reduction benefits for M_L. Although sales quantities decrease with the increase in the LCRC carbon tax rate, overall profits will increase as a result. For the distributor, cooperation leads to a reduction in the sales quantities of LCRC products as the LCRC carbon tax rate increases. Furthermore, under this cooperation model, the rise in wholesale prices for M_L exceeds the increase in retail prices for LCRC products (for detailed proof, please refer to Appendix B) under cooperation, resulting in a decrease in the unit profit of LCRC products. Consequently, the profits of the distributor also decline. Therefore, in Model B, an increase in the LCRC carbon tax rate benefits the profits of M_L and M_H, but adversely affects the profits of the distributor.

5.2. Comparative Analysis of Model N and Model B

In this section, we employ numerical methods to compare the decisions, profits, and total carbon emissions of the three participants under Models N and B. Total carbon emissions include the emissions from both LCRC and HCRC products and are defined as $CE(t) = q_L(t) - E_L(t) + q_H(t) - E_H(t)$. The parameter settings are consistent with Section 5.1, except that time is used as the horizontal axis in this part. Specifically, we reference the carbon price in China's carbon market and set $\tau_L = 0.06$to reflect the average market price of approximately 60 CNY[6]. In addition, during the simulation process, we found that the comparison of distributor profits and retail prices between the two models is affected by the LCRC carbon tax rate, so we use $\tau_L = 0.6$ to illustrate these effects. Likewise, the comparison of total carbon emissions is influenced by the decay coefficient of carbon reduction amounts ϵ; therefore, we set $\epsilon = 0.5$ to illustrate the different outcomes. The comparative results are presented in Fig. 5 – Fig. 13.

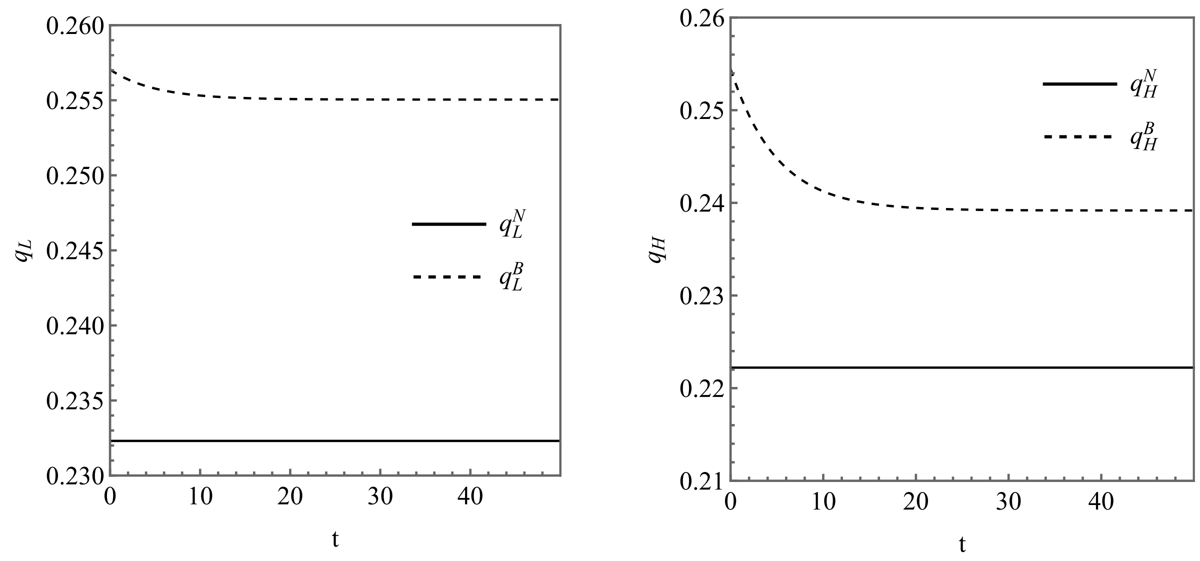


a. Carbon reduction effort of M_L b. Carbon reduction effort of M_H

Fig. 5 The variation of carbon reduction efforts in Model N and B over time

[6] https://carbonmarket.cn/ets/weekly/

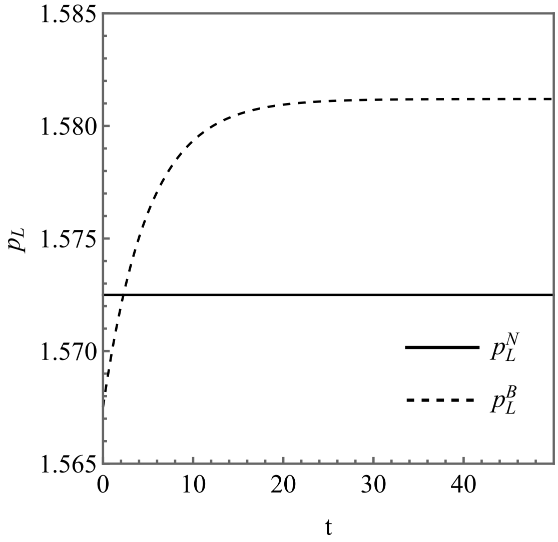
Fig. 5 highlights two key points: (i) The carbon reduction effort in Model B is higher than that in Model N. This finding is quite intuitive, as the distributor shares the carbon reduction investment costs of the manufacturers, incentivizing them to enhance their carbon reduction efforts. (ii) The carbon reduction effort in Model B increases over time and eventually stabilizes, whereas the carbon reduction effort in Model N remains constant over time. This difference arises from the distinct decision-making mechanisms in each model. In Model N, manufacturers optimize their own profits independently, determining its carbon reduction investment and wholesale pricing strategies. Since the trade-off between the cost of carbon reduction investment and the benefit of reduced carbon tax and CBAM expenses remains constant over time, manufacturers' optimal strategy is to immediately adopt a steady-state carbon reduction effort. By contrast, Model B introduces a dynamic profit-sharing mechanism based on the Shapley value, which ties each member's income to their accumulated carbon reductions. This creates an ongoing incentive to increase investment over time to gain a larger share of cooperative profits, making all strategies time-dependent.

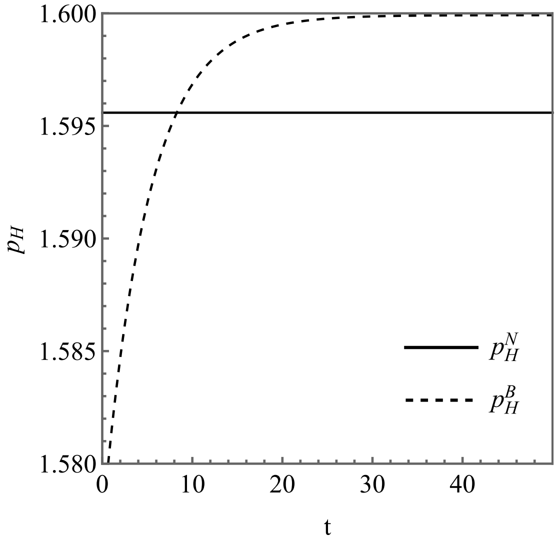


a. Sale quantities of M_L b. Sale quantities of M_H

Fig. 6 The variation of sale quantities in Model N and B over time

Fig. 6 demonstrates that the sale quantities of M_L and M_H in Model B decrease over time and eventually stabilize. However, the sale quantities of M_L and M_H are higher in Model B than in Model N. Although the carbon reduction effort increases over time, the retail prices of the distributor also rise concurrently (as shown in Fig. 7), resulting in a decrease in sale quantities over time. Nevertheless, in the cooperative model, the carbon reduction effort is significantly higher than in the non-cooperative model, which accounts for the greater sale quantities observed in Model B.

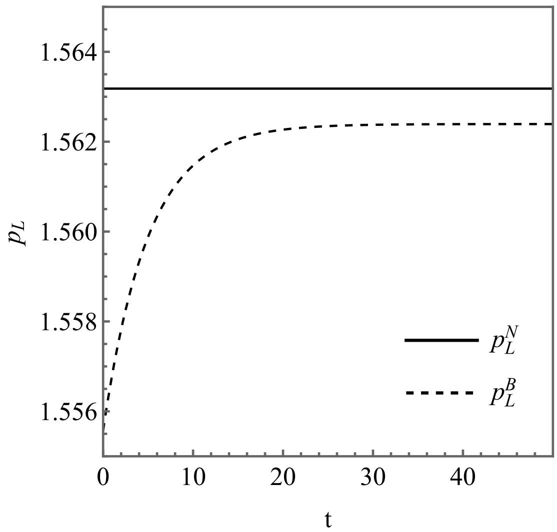


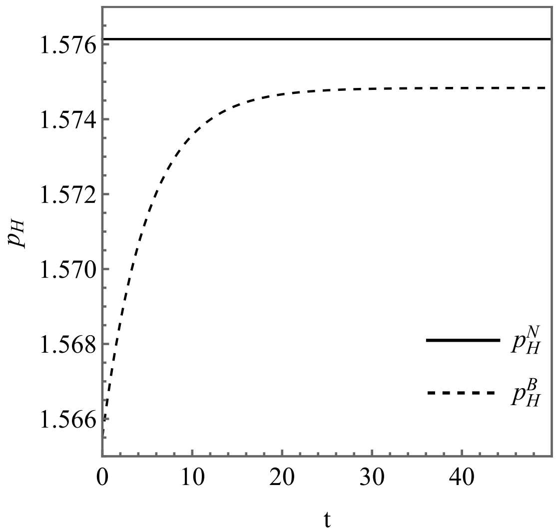


a. The retail price of the LCRC products   b. The retail price of the HCRC products

Fig. 7 The variation of retail prices in Model N and B over time ($\tau_L = 0.06$)

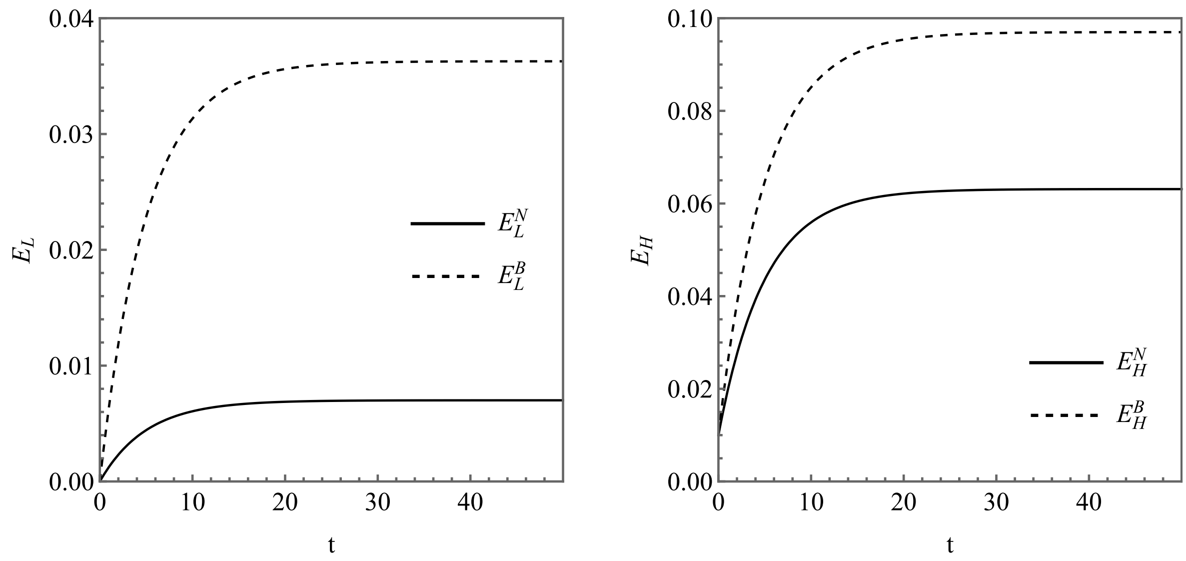
Fig. 7 illustrates that the retail prices of LCRC and HCRC products increase over time in Model B. When the carbon tax rates for LCRC and HCRC differ significantly ($\tau_H = 0.65$, $\tau_L = 0.06$), indicating a higher CBAM price, the retail prices in Model B are initially lower than those in Model N. Conversely, when the carbon tax rates for LCRC and HCRC are close ($\tau_H = 0.65$, $\tau_L = 0.6$), which corresponds to a lower CBAM price, the retail prices in Model B are lower than those in Model N (as shown in Fig. 8). However, as time progresses and the system reaches a steady state, the retail prices in Model B will exceed those in Model N. This phenomenon occurs because a higher CBAM price implies lower unit profit margins for the distributor, prompting the distributor to increase sales prices. Furthermore, in Model B, raising sales prices can enhance the carbon reduction effort of the alliance, thereby further reducing CBAM costs.





a. The retail price of the LCRC products   b. The retail price of the HCRC products

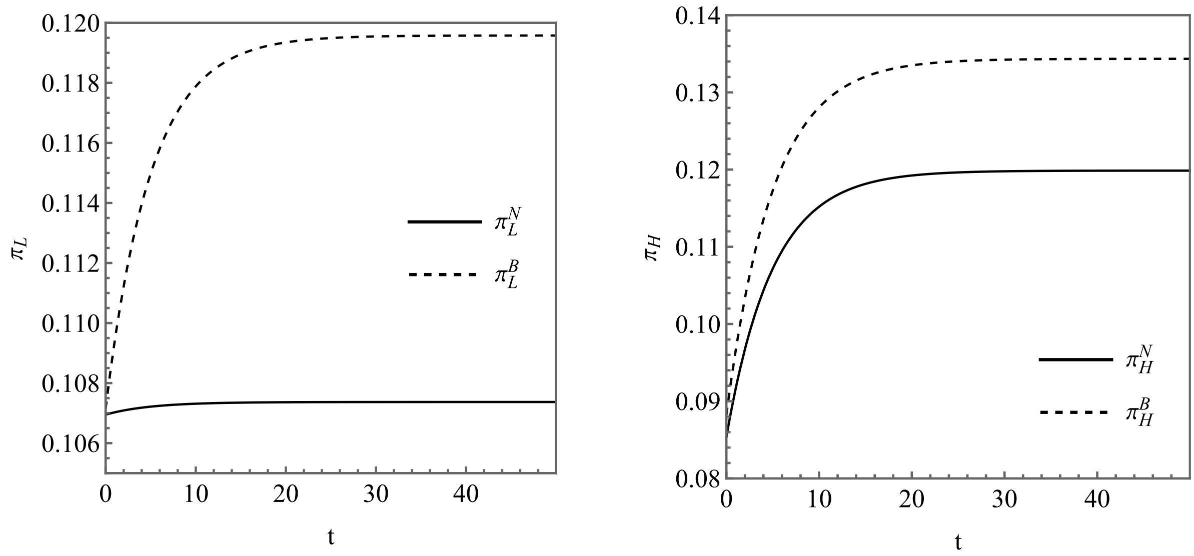
Fig. 8 The variation of retail prices in Model N and B over time ($\tau_L = 0.6$)



a. Carbon reduction amounts of M_L b. Carbon reduction amounts of M_H

Fig. 9 The variation of carbon reduction amounts in Model N and B over time

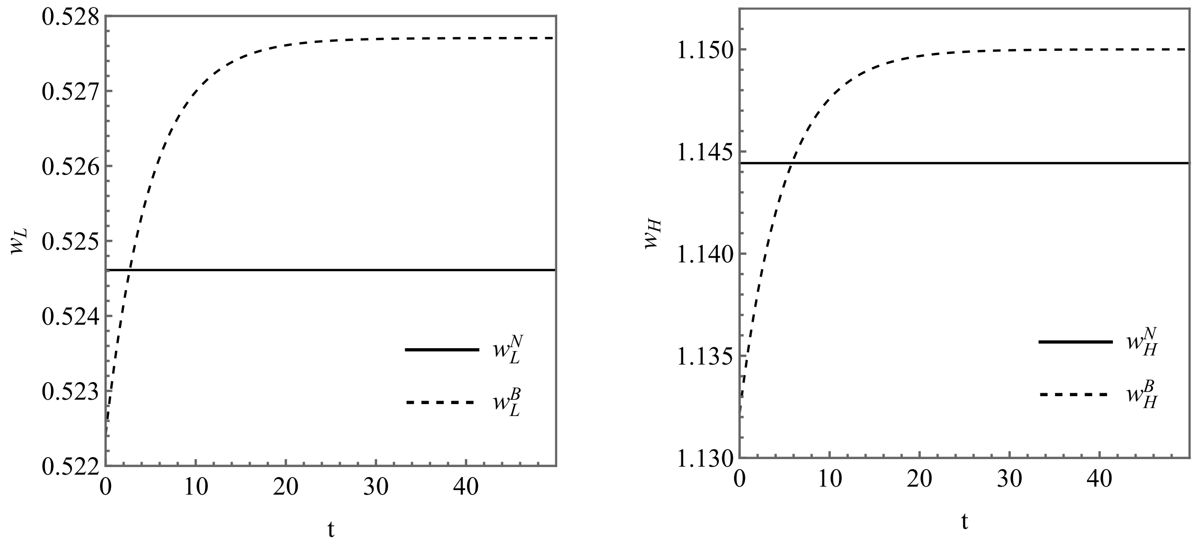
Fig. 9 indicates that, in both Model N and Model B, the carbon reduction amounts of manufacturers increase over time and eventually approach a stable state, with Model B consistently exhibiting higher values than Model N. This trend arises from the fact that manufacturers begin with a carbon reduction amount of zero and continually invest in carbon reduction during each period. Ultimately, the carbon reduction efforts and the decay rates of carbon reduction amounts reach a balance, resulting in a stable state. Given that the carbon reduction efforts in Model B are significantly higher than those in Model N, the carbon reduction amounts in Model B are consequently greater. This finding suggests that collaboration between the distributor and manufacturers in carbon reduction investments can effectively enhance carbon reduction amounts.



a. The profit of M_L b. The profit of M_H

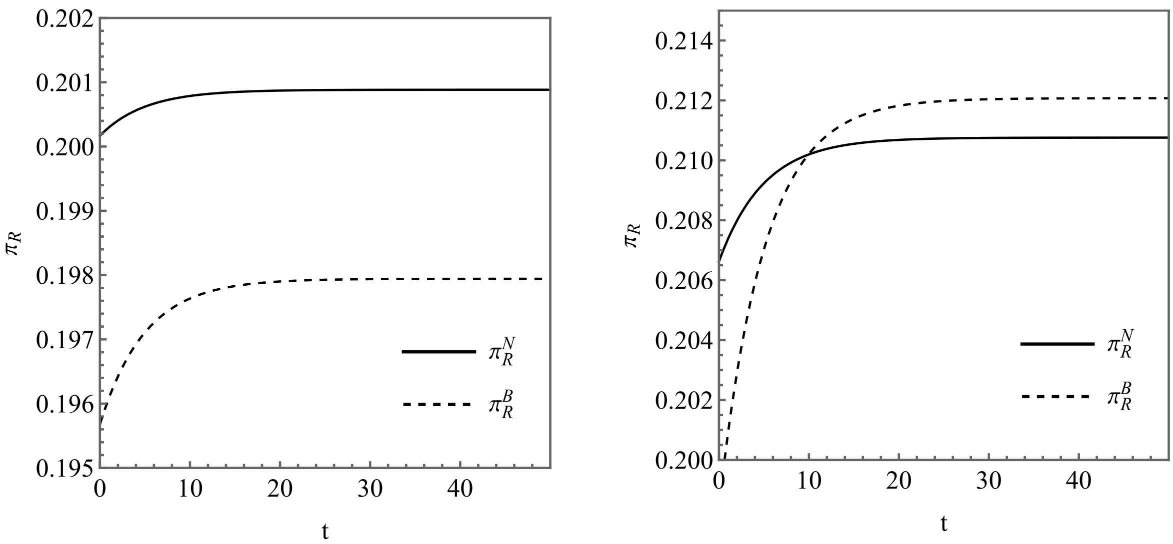
Fig. 10 The variation of manufacturers' profits in Model N and B over time

Fig. 10 indicates that, in both Model N and Model B, the manufacturers' profits increase over time and eventually approach a stable state. In Model N, the carbon reduction amounts increase over time, leading to a decrease in manufacturers' carbon costs, which in turn results in rising profits. In Model B, although sale quantities decrease over time, both carbon reduction amounts and wholesale prices increase (as shown in Fig. 9 and Fig. 11), contributing to an increase in manufacturers' unit profits and a reduction in carbon costs, thus enhancing overall profits. Furthermore, the profits of both manufacturers in Model B are higher than those in Model N. This indicates that cooperation enhances the profits of both manufacturers.



a. The wholesale price of M_L b. The wholesale price of M_H

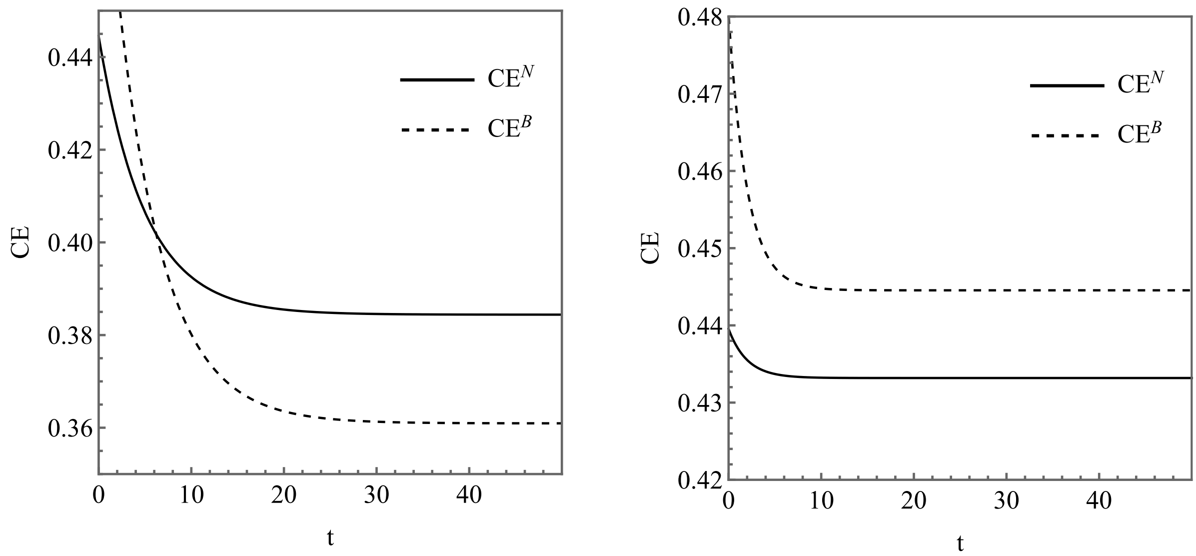
Fig. 11 The variation of wholesale prices in Model N and B over time



a. $\tau_L = 0.6$ b. $\tau_L = 0.1$

Fig. 12 The variation of the distributor's profits in Model N and B over time

Fig. 12 indicates that, in both Model N and Model B, the distributor's profits increase over time and eventually approach a stable state. In Model N, the carbon reduction amounts increase over time, leading to an upward trend in profits. Conversely, in Model B, although sale quantities decline over time, both carbon reduction amounts and retail prices rise (as shown in Fig. 7-Fig. 9), thereby enhancing overall profits. Furthermore, Fig. 12a indicates that when the carbon tax rates for LCRC and HCRC are close, corresponding to a lower CBAM price, the profits of the distributor are consistently higher in Model N. Conversely, Fig. 12b demonstrates that when there is a significant disparity between the carbon tax rates for LCRC and HCRC, corresponding to a higher CBAM price, the distributor's profits are greater in Model N in the early stage, while in the stable stage, they are higher in Model B. This variation is primarily attributed to changes in retail prices (as shown in Fig. 7 and Fig. 8). This finding indicates that, distributors achieve higher profits through non-cooperation when CBAM prices are low, while cooperation leads to greater profitability in stable stage when CBAM prices are elevated.



a. $\epsilon = 0.2$ b. $\epsilon = 0.5$

Fig. 13 The variation of the total carbon emissions in Model N and B over time

Fig. 13 shows that when the decay coefficient of carbon reduction amounts is relatively small ($\epsilon = 0.2$), the total carbon emissions under Model B are lower than those under Model N. However, when the decay coefficient is relatively large ($\epsilon = 0.5$), the total carbon emissions under Model N become lower than those under Model B. This pattern arises because cooperation increases both sale quantities (Fig. 6), which raise total carbon emissions, and carbon reduction amounts (Fig. 9), which reduce them. As shown in Appendix D, both sale quantities and carbon reduction amounts decline as ϵ increases, but the reduction in carbon reduction amounts is more substantial than the reduction in sales. Consequently, when the decay coefficient is small, the emissions reduction resulting from higher carbon reduction amounts outweighs the emissions increase caused by higher sales, leading Model B to achieve lower total carbon emissions. Conversely, when the decay coefficient is large, the emissions reduction resulting from higher carbon reduction amounts is insufficient to offset the emissions increase driven by higher sales, causing Model B to generate higher total emissions than Model N. This finding suggests that transnational supply chains aiming to deepen joint decarbonization efforts should focus on reducing the decay coefficient of carbon reduction amounts, so as to avoid the unintended outcome in which cooperation increases total carbon emissions.

6. Conclusion

In the context of global efforts to address climate change and advance low-carbon sustainable development, the carbon price disparity between less carbon-regulation countries (LCRC) and highly carbon-regulation countries (HCRC) has given rise to the Carbon Border Adjustment Mechanism (CBAM), thereby facilitating carbon reduction cooperation among supply chains. To this end, this study introduces a novel biform differential game that includes a cooperative framework in which an HCRC distributor and two manufacturers (from LCRC and HCRC) share the costs of carbon reduction, as well as a non-cooperative game theory framework aimed at maximizing the profits of the members. We utilized the Shapley value to derive the payoffs of the cooperative game, which subsequently guided the formulation of the non-cooperative game payoff function. Finally, we provided closed-form solutions for the biform differential game and conduct a dynamic analysis of the carbon reduction investments, pricing strategies, sale quantities, and profits of supply chain members in both the non-cooperative differential game and the biform differential game models. Our study draws the following interesting and meaningful conclusions.

Regarding RQ1, within Model N, an increase in CBAM prices leads LCRC and HCRC manufacturers to reduce their wholesale prices and carbon reduction efforts, resulting in lower profits and carbon reduction amounts. Distributors also lowered their retail prices and sale quantities, with their profits initially increasing and then decreasing as CBAM prices rise. In contrast, in Model B, the impact of CBAM prices on the sale quantities of LCRC products and the profits of distributors changed. As CBAM prices rise, the sales quantities of LCRC products increase, leading to a monotonous increase in distributor profits. This phenomenon primarily stems from the carbon tax rate for LCRC products having a greater impact on their retail prices than it does for HCRC products, coupled with the fact that sales quantities are more sensitive to their own prices.

Regarding RQ2, the decisions of the distributor and manufacturers evolve over time and eventually reach a stable equilibrium under the cooperation mechanism based on biform differential games, whereas their decisions are not influenced by time in the non-cooperative differential game. The cooperative mechanism enhances the carbon reduction efforts, sale quantities, and carbon reduction amounts for both LCRC and HCRC manufacturers. In the stable phase, the wholesale prices under the cooperative mechanism are higher than those in the non-cooperative model, while the retail prices exceed those of the non-cooperative model only when the CBAM prices are relatively high.

Regarding Q3, the profits of both LCRC and HCRC manufacturers are higher under the cooperation mechanism than under the non-cooperative model. For the distributor, the cooperation mechanism reduces profits when CBAM prices are low, whereas at higher CBAM prices, cooperation yields greater profits in the stable stage. From an environmental perspective, the total carbon reduction amounts under cooperation always exceed those in the non-cooperative model and continue to rise over time. However, total carbon emissions may increase or decrease depending on the decay coefficient of carbon reduction amounts: when the decay coefficient is small, cooperation reduces total emissions, whereas when it is large, cooperation leads to higher total emissions.

This study offers several actionable insights for firms and policymakers involved in the transnational supply chains under CBAM.

(1) For LCRC manufacturers:

Rising LCRC carbon tax rates strengthen carbon reduction incentives and improve profitability under both cooperative and non-cooperative environments. This suggests that LCRC manufacturers should treat domestic carbon policy tightening not as a burden but as an opportunity to enhance competitiveness in CBAM-regulated markets. Investing in long-term emission-reduction capabilities not only reduces CBAM costs but also increases consumer demand for greener products.

(2) For HCRC manufacturers:

Changes in LCRC's carbon taxation directly alter the competitive landscape. When LCRC intensifies its carbon policy, HCRC manufacturers should correspondingly raise their abatement efforts to avoid being disadvantaged. Strengthening cooperation and communication with LCRC manufacturers to jointly explore reduction technologies and strategies will facilitate mutually beneficial outcomes.

(3) For HCRC distributors:

Since cooperation is profitable only when CBAM prices are high, distributors should adopt a conditional cooperation strategy. When CBAM prices are low, a non-cooperative stance yields higher margins. Once CBAM prices reach a threshold, however, co-investing in emission reduction and sharing abatement costs becomes a superior long-term strategy. Moreover, distributors should be aware that cooperation does not always guarantee lower total emissions; when the decay coefficient of carbon reduction amounts is high, cooperation may inadvertently increase total emissions. Thus, distributors should encourage technological upgrades that reduce the decay rate of carbon reduction to ensure that cooperation generates both economic and environmental benefits.

(4) For policymakers:

The results highlight that coordinated carbon reduction within supply chains can amplify the environmental effectiveness of CBAM, but this effect depends critically on the durability of carbon reduction technologies. Policies that support cross-border technological cooperation, such as joint R&D, preferential financing for long-lasting abatement technologies, or certification systems that reward slow-decay carbon reduction stocks, can help ensure that cooperation consistently lowers total emissions without undermining trade competitiveness.

Although this study contributes to understanding dynamic carbon-reduction cooperation under CBAM, several limitations present opportunities for further research. First, the analysis assumes stable policy parameters such as carbon taxes and CBAM prices. In practice, firms face policy uncertainty, phased CBAM implementation, and evolving carbon-accounting rules. Future models could incorporate stochastic CBAM prices or policy uncertainty to capture the transitional risks firms confront during decarbonization. Second, this study adopts Shapley-based cooperation with rational agents, but does not model behavioral factors such as fairness concerns or bounded rationality. Exploring contract-theoretic extensions, including relational contracts, or fairness-driven bargaining, would offer richer insights.

Conflict of Interests statement

The authors declare no competing interests.

Data availability statement

There is no data used in this study.

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