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Manufacturer encroachment and carbon reduction decisions considering cap-and-trade policy and retailer investment

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Abstract Low-carbon regulation and market competition present new opportunities and challenges for supply chain firms, emphasizing the significance of carbon reduction and channel encroachment in enhancing competitiveness. This study formulates various game models to evaluate manufacturers' encroachment strategies (with or without encroachment) under different conditions of low-carbon investment by retailers. It investigates the operational decisions and carbon abatement strategies of firms under various scenarios. The findings reveal that encroachment elevates unit abatement levels but decreases wholesale prices and retailer profits when unit encroachment costs are below certain thresholds. In contrast, the manufacturer consistently benefits from channel encroachment. Retailer-initiated low-carbon investments can motivate manufacturers to reduce emissions. A lower carbon price potentially offers financial advantages to retailer engaging in such investments. Additionally, the likelihood of reduced environmental damage postchannel encroachment, compared to preprofessional encroachment, increases when the retailer invests in low-carbon initiatives. The retailer's profit is inversely related to the carbon price, and a higher carbon price can strengthen the incentive effect of low-carbon investment on the manufacturer's abatement endeavors.

Keywords carbon cap-and-trade, channel encroachment, emission reduction, low-carbon investment

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1 Introduction

Environmental regulations play a central role in compelling firms to improve their production processes, aiming to reduce the toxicity of waste materials and the volume of emissions (Xiao et al., 2019). For instance, strategies such as carbon cap-and-trade (C&T) have been adopted in various regions, including the European Union, China, and New Zealand, to curb carbon dioxide-based greenhouse gas emissions, resulting in commendable results (Huang et al., 2021).

Within the framework of C&T, firms' carbon emissions are constrained by initial carbon allowances set by regulators. However, these firms have the option to trade emission allowances within the carbon market, indirectly altering their emission limits (Anand and Giraud-Carrier, 2020; Wang et al., 2022). An illustrative case occurred in early 2019 when Fiat Chrysler Automobiles and General Motors entered into carbon credit purchase agreements with Tesla to meet emission requirements. Under the C&T policy's regulations, reducing carbon emissions (e.g., through production cuts and low-carbon innovation) or acquiring additional carbon credits have proven effective in addressing the shortage of carbon quotas. Consequently, C&T policy has had a discernible effect on firms' business activities. For instance, home appliance manufacturers such as Haier and GREE have actively embraced green and low-carbon technologies while developing energy-efficient products (Yu et al., 2022).

Retail firms, alongside their manufacturing counterparts, are increasingly engaged in efforts to reduce their carbon emissions. Prominent retailers such as Walmart and TESCO exemplify this trend, achieving carbon reduction by advocating for and promoting low-carbon products and participating in green public welfare initiatives (Ji et al., 2017). Research and real-life cases have demonstrated that firms' environmental investments influence consumers' purchasing decisions (Murali et al., 2019; Hosseini-Motlagh et al., 2021). For instance, Beijing Yuntong Jiabao Automobile Sales and Service Co., Ltd. experienced a significant 50% increase in

customer foot traffic due to the implementation of low-carbon enhancements, including energy-saving retrofits and the adoption of green electricity solutions.

Simultaneously, advancements in logistics and internet technology have empowered more manufacturers to encroach upon distribution channels. This expanded participation has created a nuanced landscape characterized by both competition and cooperation with retailers (Arya et al., 2007). For example, Coca-Cola not only distributes its products through retailers such as TESCO but also establishes direct sales channels to reach consumers. Moreover, influenced by low-carbon initiatives from retailers such as TESCO, Coca-Cola has transitioned its beverage packaging to returnable or reusable bottles (Peng, 2011).

Conventional wisdom suggests that manufacturer encroachment may reduce retailers' profitability and lead to conflicts between manufacturers and retailers (Ha et al., 2016). However, a body of research argues that encroachment enhances manufacturers' flexibility in navigating diverse channels, opening up new markets (Li et al., 2021a). Despite the advantages and disadvantages associated with encroachment, existing research has paid limited attention to the emerging context of low-carbon development within supply chains. In a sustainable society, environmental considerations have become crucial for firms when selecting a dual-channel structure (Yang et al., 2019).

In light of the above background, retailers implementing green initiatives can create numerous business opportunities and enhance the competitiveness of retail channels (Xia et al., 2023). Such implementation can influence not only the competitive dynamics between the retail and direct sales channels after manufacturer encroachment but also the overall market demand to some extent. Given that manufacturers are constrained by their total carbon quotas, high demand implies increased carbon emissions. Consequently, fluctuations in market demand stemming from channel competition will inevitably affect manufacturers' production, pricing, emission reduction, and encroachment strategies. Furthermore, carbon abatement or low-carbon investment raises the production and operational costs of the supply chain, impacting the manufacturer's choice of sales model (Zhang et al., 2020; Liu and Ke, 2021). The effect of low-carbon development permeates various aspects, including power production costs, production plans, power prices, and corporate philosophies. The influence of the EU carbon emissions trading system on the power industry serves as an illustrative example. Given the interplay of these factors, manufacturers must make optimal decisions regarding channel encroachment, abatement, and production under various low-carbon investment scenarios for retailers, considering the potential interaction between channel encroachment and abatement decisions.

This study explores the C&T mechanism and

investigates the channel encroachment and carbon reduction strategies of manufacturers under two scenarios: one where the retailer makes low-carbon investments and another where it does not. It is worth noting that the retailer's low-carbon investment pertains to actions independent of the manufacturer's abatement activities, such as participation in environmental initiatives and the adoption of green energy. Specifically, this study addresses the following questions: (1) Given different low-carbon investment scenarios for retailers, should the manufacturers pursue channel encroachment? (2) Considering the various encroachment strategies of the manufacturer, should the retailer invest in low-carbon initiatives? (3) How does the C&T policy impact decision-making within supply chain firms?

In response to the challenges outlined earlier, this study developed a series of game-theoretical models within the context of the supply chain. In these models, the manufacturer initiates carbon reduction efforts under the C&T mechanism while simultaneously deliberating the feasibility of introducing direct sales channels. Simultaneously, the retailer determines its options for low-carbon investment. Specifically, this study considers four types of models: manufacturer nonencroachment (NN) or encroachment (NE) when the retailer has no low-carbon investment and manufacturer nonencroachment (LN) or encroachment (LE) when the retailer has low-carbon investment. Based on these models, this study explores the impacts of the manufacturer's encroachment decision, the retailer's low-carbon investment decision, and the strategic interaction between the two decisions. This analysis includes the supply chain equilibrium strategy, firm profit, and environmental damage under different scenarios. Additionally, the study fully considers the roles played by C&T mechanisms, channel competition, and abatement cost coefficients in this analysis.

This study has arrived at several key conclusions. First, across all the scenarios, there is an inverse correlation between the unit abatement level, market demand, and profits of both firms and the initial level of carbon emissions. This highlights the challenges faced by firms with high initial emissions in realizing their abatement potential under C&T policy and the potential for profit losses throughout the supply chain. Second, when the unit encroachment cost remains low, manufacturer encroachment can increase the unit abatement level and reduce wholesale and sales prices. However, the retailer can benefit from manufacturer encroachment only when the unit encroachment cost is high. Third, irrespective of manufacturer encroachment, low-carbon investment by retailers emerges as a powerful driver of abatement, offering a practical avenue for downstream retail entities to influence upstream production enterprises toward abatement. Furthermore, when the retailer makes low-carbon investments, the likelihood of reduced environmental damage after channel encroachment

increases. Fourth, irrespective of encroachment, the manufacturer can secure increased profits when the retailer invests in low-carbon initiatives. Finally, a moderate increase in carbon prices can stimulate firms to intensify their abatement efforts, but excessively high carbon prices can dampen enthusiasm for abatement.

This study contributes and innovates in several significant ways. First, it enriches the discussion on channel encroachment by examining manufacturer encroachment within the C&T framework. Second, unlike the previous literature that has focused primarily on manufacturers' carbon abatement (e.g., Wang et al., 2022; Deng et al., 2023; Xu et al., 2023), this study incorporates retailers' low-carbon investment into the game model. Additionally, the paper explores the interactive effects between manufacturer encroachment and carbon abatement strategies, as well as the role of retailers' low-carbon investment in manufacturers' decision-making. Third, in contrast to existing studies that consider retailer behavior within the same channel structure (e.g., Liu et al., 2022; Shi et al., 2023a), this study analyzes the role of retailer low-carbon investment in both a single retail channel (without channel encroachment) and a dual-channel (with channel encroachment) scenario, offering a comprehensive perspective. Furthermore, this study highlights the formation of a cooperative-competitive relationship between the manufacturer and the retailer after channel encroachment, allowing for the exploration of carbon reduction issues in a cooperation supply chain constrained by C&T mechanisms.

The remainder of this paper unfolds as follows: Section 2 provides an overview of the relevant literature. Section 3 outlines the problem and explains the modeling assumptions. Section 4 constructs, solves, and analyses the game model. In addition, Section 5 compares and analyses the equilibrium results of the models. Section 6 presents a numerical analysis, and Section 7 extends the model to verify the robustness of the conclusions. Finally, Section 8 presents the research findings and management insights. All proof processes are in Appendix A.

2 Literature review

This study is primarily aligned with two significant streams of literature: corporate carbon reduction and manufacturer/supplier channel encroachment. Consequently, we will conduct a thorough review of the literature within these two domains and subsequently emphasize the unique contributions and innovations that this study brings to these areas.

2.1 Supply chain carbon reduction and operations

In the era of low-carbon sustainability, numerous

researchers have turned their attention to the operational and carbon reduction decisions made by firms operating in emission-dependent supply chains (Shi et al., 2023a). For instance, Plambeck (2012) argued convincingly that firms can simultaneously achieve economic benefits while contributing to environmental goals through carbon reduction initiatives. Additionally, Bai et al. (2019) conducted a comparative analysis of corporate profits and carbon emissions between centralized and decentralized models in a low-carbon supply chain focusing on deteriorated goods comprising a manufacturer and two competing retailers. Their findings revealed that in a decentralized mode, carbon emissions may be lower than in a centralized setup, and revenue-sharing contracts can facilitate system coordination.

Given the pivotal role of government regulations, several scholars have investigated corporate abatement and operations within the framework of low-carbon regulatory policies. Notably, C&T policy has attracted significant attention as an effective abatement measure (Yang et al., 2020). For example, Sabzevar et al. (2017) constructed a Cournot game model involving two competing producers and examined the effect of the C&T policy on the profitability of both firms. Their research revealed that the C&T mechanism does not necessarily lead to an increased market share for firms with low emission intensity. Building upon the C&T mechanism, Liu et al. (2022) analyzed the influence of information sharing on carbon abatement in maritime supply chains, considering the interactive effects between information sharing and firms' optimal strategies for adopting carbon abatement technologies. Their findings underscored that information sharing alone cannot reduce overall carbon emissions, but fluctuations in carbon prices can significantly influence firms' strategies for adopting abatement technologies.

Furthermore, Wang et al. (2022) investigated the effect of carbon prices and their uncertainty on manufacturers' abatement strategies, revealing a positive correlation between abatement levels and carbon credit trading prices. Wang and Wu (2021) and Mondal and Giri (2022) examined the effects of different decision-making models (e.g., centralized and decentralized decision-making) on the abatement plans of supply chain members under C&T policy. Additionally, considering the development of the sharing economy and the associated carbon emissions issues arising from the rebalancing operations of shared bicycles, Qin et al. (2023) proposed an optimization model to reduce carbon emissions during rebalancing operations, achieving a substantial 57.5% reduction in carbon emissions for the public transportation system in Beijing.

Moreover, Shi et al. (2023a) explored the effect of retailer purchase commitments on the economic and environmental performance of a supply chain that includes a

capital-constrained supplier. They discovered that procurement commitments have a negative effect on per-unit carbon abatement and overall carbon reduction within the supply chain. In the context of the platform economy, Xu et al. (2023) determined the optimal operational decision-making problem for manufacturers in a platform supply chain based on the C&T mechanism, assessing the manufacturer's choice of platform model (market model or resale model) under conditions of demand disruption.

Furthermore, as the importance of carbon neutrality has gained recognition among governments and organizations (Jiang et al., 2023; Liu et al., 2023), scholars have also begun analyzing carbon abatement issues within the context of carbon neutrality. For instance, Su et al. (2023) explored the role of technological innovation in achieving carbon neutrality, revealing that technological innovation can optimize energy structures, reduce carbon emissions, and serve as a crucial pillar in achieving carbon neutrality. Additionally, Deng et al. (2023) investigated the effect of carbon trading prices on the choice of a manufacturer's financing strategy in both carbon-neutral and noncarbon-neutral scenarios. Their findings indicated that as abatement efficiency improves, manufacturers tend to choose internal financing in carbon-neutral scenarios and external financing in noncarbon-neutral scenarios.

Most of the literature on low-carbon supply chains has focused primarily on noncompetitive scenarios (e.g., Mondal and Giri, 2022; Wang et al., 2022; Shi et al., 2023a), with only limited research examining the effect of competition on firms' abatement efforts (e.g., Sabzevar et al., 2017; Xu et al., 2023). In contrast, this research investigates decision-making issues related to the abatement and pricing of firms in supply chains in both preencroachment (no-channel competition) and postencroachment (channel competition) scenarios. Moreover, the effect of retailer behavior on carbon abatement or operational strategies in supply chains has attracted the attention of scholars (Liu et al., 2022; Shi et al., 2023a). This paper introduces a novel dimension by incorporating the retailer's low-carbon investment into the analytical model and exploring its influence on the manufacturer's abatement and encroachment decisions. Additionally, while previous studies have analyzed the influence of C&T mechanisms, carbon trading prices, and technological innovation on corporate abatement strategies (Wang et al., 2022; Deng et al., 2023; Su et al., 2023), this study uniquely investigates the role of C&T mechanisms in retailer low-carbon investment decisions and manufacturer encroachment decisions.

2.2 Supply chain encroachment

Scholars have undertaken a series of investigations into channel encroachment within supply chains. Yoon (2016) elucidated that following encroachment, the manufacturer

might engage in self-serving cost reduction investments, leading to additional benefits that spill over to the retailer in the form of wholesale prices, ultimately enhancing the retailer's profits. Zhang et al. (2019) revealed that, irrespective of the fixed cost of encroachment, manufacturer encroachment consistently disadvantages the dominant retailer while benefiting the manufacturer itself. Furthermore, Huang et al. (2018) examined the strategic interaction between retailer information sharing and supplier encroachment, showing that information sharing could weaken the retailer's information advantage, impacting its expected returns. However, it can also act as a deterrent to supplier encroachment, thus increasing the retailer's expected returns.

Zheng et al. (2019) applied game theory to examine the effect of manufacturer encroachment on retailer revenue under varying power structures. Their results indicated that, under symmetric initial demand conditions, the manufacturer generally leans toward encroachment, while the retailer can only benefit when channel competition is evenly balanced. Liu et al. (2021) explored supplier encroachment decisions in the context of downstream competition involving multiple retailers within the supply chain. Their findings demonstrated that when the number of retailers is below a certain threshold, channel encroachment can be advantageous for both suppliers and retailers. However, when the number of retailers surpasses this threshold, channel encroachment may harm retailer profits.

Similarly, Zhang et al. (2020) considered scenarios where a manufacturer opens a direct sales channel to implement encroachment and discussed pricing and abatement issues within the supply chain under three channel structures: a single retail channel, a single direct sales channel, and a dual channel. Their conclusions revealed that in the latter two channel structures, the sale of low-carbon products by retailers can lead to higher profits for manufacturers if consumers possess a moderate level of environmental preferences. Furthermore, Li et al. (2021c) analyzed the effects of consumer green preferences and product substitutability on manufacturers' encroachment decisions and supply chain members' profits and showed that improvements in both factors enable manufacturers to attain increased profits from encroachment.

In the context of medical institutions expanding their services to online platforms, Xu et al. (2022) investigated the effect of physicians' online and offline reputations on their behavior in online channel services and observed a negative correlation between physicians' offline reputation and their online consultation behavior. Furthermore, Shi et al. (2023b) considered the establishment of an e-commerce department by a manufacturer to implement channel encroachment, exploring the channel structure selection problem under two scenarios of centralized and decentralized decision-making within the organization. Their results indicated that an integrated structure can achieve a win-win situation for supply chain members

under certain conditions. Additionally, Lu et al. (2023) assessed the issue of channel encroachment implemented by green manufacturers through short video platforms, highlighting the advantages of these platforms in providing consumer environmental information. Their study showed that retailers can benefit from manufacturer channel encroachment when the platform implements information sharing. Moreover, Tong et al. (2023) examined the channel encroachment problem in a supply chain using a signal game, assuming that the manufacturer can privately observe market demand information. They found that channel encroachment may lead to a double-loss result for both the manufacturer and the retailer when the manufacturer possesses an information advantage.

The literature review reveals that the majority of current studies on channel encroachment have been conducted in traditional supply chain operation scenarios. These studies have explored the effect of channel encroachment on firms' profits and the relationship between information sharing and channel encroachment (e.g., Huang et al., 2018; Tong et al., 2023; Shi et al., 2023b). Only a limited number of studies have examined channel encroachment and related operational issues in the context of low-carbon considerations (e.g., Zhang et al., 2020; Li et al., 2021c). Diverging from the literature, this study conducts research within the framework of a low-carbon supply chain while simultaneously considering the role of C&T mechanisms. Unlike the works of Zhang et al. (2020) and Li et al. (2021c), this research explores manufacturers' encroachment and abatement strategies, both with and without retailers' low-carbon investment. Additionally, the study investigates the effect of C&T mechanisms on manufacturer encroachment decisions and explores the complex interplay between abatement and encroachment decisions. Importantly, very few studies have explored the interaction between different decisions within firms that implement encroachment.

3 Methodology

3.1 Problem definition and assumptions

In the context of the C&T mechanism, the manufacturer assumes the position of the supply chain leader, carrying the responsibility for emissions reduction in the production process. Conversely, the retailer adopts the role of the follower while also having the opportunity to engage in low-carbon investments. These investments may include various initiatives, such as participation in environmental protection efforts, the adoption of clean energy solutions, and the implementation of low-carbon marketing strategies. If the manufacturer does not implement channel encroachment, then the retailer procures products from

the manufacturer at price w and retails them to the end consumers at a price designated p_r . If the manufacturer opts to establish a direct sales channel for the purpose of encroachment, the pricing of the product within the direct sales channel is denoted as p_d . Demand in the retail channel and the manufacturer's direct channel are denoted as q_r and q_d , respectively. Notably, the implementation of channel encroachment by the manufacturer leads to the emergence of a dynamic of competition and cooperation between the two firms.

This study adopts the assumption of risk neutrality for both firms and sets the unit production cost and retail channel sales cost to 0. The symbol c represents the manufacturer's unit encroachment cost, which corresponds to the unit sales cost of the direct sales channel (Arya et al., 2007; Wang and Li, 2021). The unit cost associated with the direct selling channel serves to characterize the retailer's relative advantage in sales. Additionally, the initial level of unit carbon emissions of the manufacturer is denoted as e , the total carbon emission is represented by E , the unconstrained emission quota obtained under the C&T mechanism is indicated as G , and the carbon price is p_e . Among them, $E = (e - x)(q_r + q_d)$. Referring to Xia et al. (2018) and He et al. (2021), the manufacturer's abatement investment is a one-time cost, which is denoted as $hx^2/2$. Here, h represents the abatement cost coefficient, and x signifies the abatement level of the unit product. Taking into account real-world observations and relevant literature, this study also assumes that the low-carbon investment of a retailer manifests through its selection of one or several fixed-cost-related low-carbon options (Li et al., 2021b). In scenarios where the retailer engages in low-carbon investment, the fundamental demand of the retail channel becomes $a + m$. Here, a represents substantial market potential, $m(m > 0)$ serves as an exogenous variable indicating the level of expansion of retail channel demand, and the exogenous discrete variable F denotes the cost of low-carbon investment (Li et al., 2020; Yang et al., 2021). Furthermore, to ensure the practical significance of the research, this study reasonably assumes that $h > p_e^2(3 - 2b)/(4 - 2b)^2$. This assumption implies that the abatement cost coefficient must be set at a high level to accurately represent the challenging and costly nature of abatement. Similar assumptions have been made in the studies of Luo et al. (2016), Ji et al. (2017), and Sun et al. (2023). In Section 7, this study will assess the validity of these findings in various scenarios where m becomes endogenous.

3.2 Demand function

Expanding on the previous analysis, this study utilizes a linear demand function, a commonly employed model in the field of operations management, to illustrate the connection between price and demand (Li et al., 2020;

Yang et al., 2021; Zhang et al., 2023). Specifically, the demand function of the retail channel in the NN model is $p_r^{NN} = a - q_r$. In addition, the demand functions of the retail channel and direct sales channel in the NE model are $p_r^{NE} = a - q_r - bq_d$ and $p_d^{NE} = a - q_d - bq_r$, respectively. The demand function of the retail channel in the LN model is $p_r^{LN} = a + m - q_r$. The demand functions of the retail channel and direct sales channel in the LE model are $p_r^{LE} = a + m - q_r - bq_d$ and $p_d^{LE} = a - q_d - bq_r$, respectively. Within this framework, the parameter $0 \leq b \leq 1$ captures the level of competition between the two channels.

3.3 Decision sequence

In various game scenarios, the decision sequence of the manufacturer and the retailer unfolds as follows: (1) The manufacturer, as the dominant entity, decides whether to initiate encroachment. (2) In the absence of encroachment, the manufacturer initially selects the unit abatement level x and subsequently determines the wholesale price w . In cases involving encroachment, the manufacturer first sets the unit abatement level x and then simultaneously sets the wholesale price w and direct selling price p_d . (3) The retailer determines the retail price p_r . The optimal strategies within all the models are deduced through the application of backward induction.

For convenience, we designate $i = \{NN, NE, LN, LE\}$ to denote the four models considered in this study. Among these expressions, $j = \{NN, LN\}$ corresponds to the two models lacking manufacturer encroachment, and $k = \{NE, LE\}$ represents the two models including manufacturer encroachment, with an asterisk (*) denoting the optimal solution. Furthermore, subscripts m and r signify the manufacturer and retailer, respectively.

4 Models and analytical results

4.1 No low-carbon investment and no encroachment

In the NN scenario, the manufacturer distributes its products solely to consumers through the retailer channel, without any low-carbon investment by the retailer. In this

context, the objective functions of the two firms are as follows:

$$\pi_m^{NN} = wq_r - p_e(e - x)q_r + p_eG - \frac{1}{2}hx^2, \quad (1)$$

$$\pi_r^{NN} = (p_r^{NN} - w)q_r. \quad (2)$$

Lemma 1: In the NN scenario, the optimal unit abatement levels, wholesale prices, and selling prices are $x^{NN*} = A_1 p_e$, $w^{NN*} = a - 2hA_1$, and $p_r^{NN*} = a - hA_1$, respectively, where $A_1 = \frac{(a - ep_e)}{4h - p_e^2}$. Correspondingly, we can obtain the optimal profits $\pi_m^{NN*} = wq_r - p_e(e - x^{NN*})q_r + p_eG - h(x^{NN*})^2/2$ and $\pi_r^{NN*} = (p_r^{NN*} - w^{NN*})q_r$.

4.2 Non-low-carbon investment but encroachment

In the NE scenario, the manufacturer sells the product through the retailer while concurrently creating a direct sales channel. This dynamic results in competition between the manufacturer and the retailer. However, the retailer still refrains from making low-carbon investments. In this context, the objective functions of the two firms are as follows:

$$\pi_m^{NE} = (p_d^{NE} - c)q_d + wq_r - p_e(e - x)(q_d + q_r) + p_eG - \frac{1}{2}hx^2, \quad (3)$$

$$\pi_r^{NE} = (p_r^{NE} - w)q_r. \quad (4)$$

Lemma 2: In the NE scenario, the optimal unit abatement levels, wholesale prices, and selling prices are

$$x^{NE*} = \frac{p_e((a - ep_e)B_1 - (2 - b)c)}{-2B_2h - B_1p_e^2},$$

$$w^{NE*} = \frac{2B_2h(a + ep_e) + (2aB_1 + (-2 + b)c)p_e^2}{4B_2h + 2B_1p_e^2},$$

$$p_d^{NE*} = \frac{2hB_2(a + c + ep_e) + (2aB_1 + c - bc)p_e^2}{4B_2h + 2B_1p_e^2},$$

and

$$p_r^{NE*} = \frac{2h(a(-3 + b + b^2) - bc) + 2hep_e(b^2 - b - 1) + (2aB_1 + (b - 1)c)p_e^2}{4B_2h + 2B_1p_e^2},$$

respectively, where $B_1 = 3 - 2b$ and $B_2 = -2 + b^2$. Correspondingly, we can obtain the optimal profits $\pi_m^{NE*} = (p_d^{NE*} - c)q_d + w^{NE*}q_r - p_e(e - x^{NE*})(q_d + q_r) + p_eG - h(x^{NE*})^2/2$ and $\pi_r^{NE*} = (p_r^{NE*} - w^{NE*})q_r$.

4.3 Low-carbon investment but no encroachment

In the LN scenario, the retailer makes a low-carbon investment, but the manufacturer has no channel encroachment. In this context, the objective functions of

the two firms are as follows:

$$\pi_m^{LN} = wq_r - p_e(e-x)q_r + p_eG - \frac{1}{2}hx^2, \quad (5)$$

$$\pi_r^{LN} = (p_r^{LN} - w)q_r - F. \quad (6)$$

Lemma 3: In the *LN* scenario, the optimal unit abatement levels, wholesale prices, and selling prices are $x^{LN^*} = A_2p_e$, $w^{LN^*} = a + m - 2hA_2$, and $p_r^{LN^*} = a + m - hA_2$, respectively, where $A_2 = \frac{(a+m-ep_e)}{4h-p_e^2}$. Correspondingly, we can obtain the optimal profits $\pi_m^{LN^*} = w^{LN^*}q_r - p_e(e-x^{LN^*})q_r + p_eG - \frac{h(x^{LN^*})^2}{2}$ and $\pi_r^{LN^*} = (p_r^{LN^*} - w^{LN^*})q_r - F$.

4.4 With low-carbon investments and encroachment

In the *LE* scenario, the manufacturer opens a direct sales channel where the retailer has a low-carbon investment. In this context, the objective functions of the two firms

are as follows:

$$\pi_m^{LE} = (p_d^{LE} - c)q_d + wq_r - p_e(e-x)(q_d + q_r) + p_eG - \frac{1}{2}hx^2, \quad (7)$$

$$\pi_r^{LE} = (p_r - w)q_r^E - F. \quad (8)$$

Lemma 4: In the *LE* scenario, the optimal unit abatement levels, wholesale prices, and selling prices are

$$x^{LE^*} = \frac{p_e((a-ep_e)B_1 + (-2+b)c + m - bm)}{-2B_2h - B_1p_e^2}$$

$$w^{LE^*} = \frac{1}{2} \left(a + m + \frac{p_e(-2hB_2e + (-aB_1 - (-2+b)c - m + bm)p_e)}{-2B_2h - B_1p_e^2} \right),$$

$$p_d^{LE^*} = \frac{2hB_2(a+c+ep_e) + (2aB_1 + c - bc + m - bm)p_e^2}{4B_2h + 2B_1p_e^2},$$

and

$$p_r^{LE^*} = \frac{2h[(a+m)(-3+b^2) + (a-c)b + (-b+b^2-1)ep_e] + 2[2aB_1 - (1-b)c + 5m - 3bm]p_e^2}{4B_2h + 2B_1p_e^2},$$

respectively, where $B_1 = 3 - 2b$ and $B_2 = -2 + b^2$. Correspondingly, we can obtain the optimal profits $\pi_m^{LE^*} = (p_d^{LE^*} - c)q_d + w^{LE^*}q_r - p_e(e-x^{LE^*})(q_d + q_r) + p_eG - \frac{h(x^{LE^*})^2}{2}$ and $\pi_r^{LE^*} = (p_r^{LE^*} - w^{LE^*})q_r - F$.

4.5 Model analysis

Based on equilibrium strategies across diverse scenarios, this study derives the following corollaries to investigate the effects of abatement cost coefficients and the initial level of unit carbon emissions.

Corollary 1. (1) Across all the scenarios, there exists an inverse correlation between the unit abatement level and the abatement cost coefficient. This correlation aligns with real-world scenarios, indicating that higher abatement cost coefficients correspond to lower abatement levels. (2) Wholesale and two-channel sales prices exhibit a positive correlation with the abatement cost coefficient. This observation explains why products with a high level of environmental protection often come with higher price tags. (3) The optimal profits of both firms are negatively correlated with the abatement cost coefficient. Elevated abatement cost coefficients result in increased manufacturing costs, thereby reducing the overall profits of both firms.

Corollary 2. (1) The unit abatement level is negatively correlated with the initial level of unit carbon emissions. Intuitively, a higher initial level implies greater abatement

potential for the manufacturer. However, a paradox emerges under C&T policy. Specifically, as the initial level of unit carbon emissions increases, the associated unit cost of carbon emissions for the manufacturer also increases, hindering the manufacturer's ability to allocate sufficient financial resources toward abatement efforts. (2) Furthermore, wholesale and retail prices exhibit a positive correlation with the initial unit carbon emission level. This indicates that, from both an environmental and pricing perspective, products characterized by high initial levels of unit carbon emissions face challenges in gaining consumer preference within the framework of C&T policies. (3) Both types of profitability demonstrate a negative correlation with the initial unit carbon emission level. Taken together, these findings suggest that a stringent C&T mechanism may increase the cost for abatement firms, potentially impeding their ability to achieve substantial emissions reduction.

5 Comparative analysis

Based on the abovementioned corollaries, this section seeks to assess the effects of manufacturer encroachment and retailer low-carbon investment on the optimal strategies within the supply chain. This analysis will be conducted by comparing equilibrium strategies across different scenarios.

5.1 Impact of manufacturer encroachment

Proposition 1. The optimal unit level of abatement before and after manufacturer encroachment exhibits the following relationship:

- (1) $x^{NE^*} > x^{NN^*}$ if $c < c_1$; otherwise, $x^{NE^*} < x^{NN^*}$;
- (2) $x^{LE^*} > x^{LN^*}$ if $c < c_2$; otherwise, $x^{LE^*} < x^{LN^*}$. Here, $c_1 = 2h(2-b)(a-ep_e)/(4h-p_e^2)$, and $c_2 = (2h[(a-ep_e)(2-b)-bm]+mp_e^2)/(4h-p_e^2)$.

Proposition 1 highlights a significant shift in the optimal unit abatement level within the supply chain before and after channel encroachment actions. Specifically, after encroachment, the unit abatement level surpasses the preencroachment level when the unit cost of encroachment is below a specific threshold. However, if the unit cost of encroachment exceeds this threshold, the unit abatement level following encroachment becomes lower than the level observed before encroachment. The threshold is influenced positively by the low-carbon investment effect of the retailer. In scenarios with lower unit encroachment costs, the increase in the selling price resulting from encroachment is mitigated. However, encroachment triggers an increase in market demand, leading to higher overall carbon emissions from the manufacturer. Consequently, the manufacturer is compelled to increase the per-unit abatement level to comply with the constraints of the C&T policy. Conversely, when the unit encroachment cost surpasses a certain threshold, the financial burden of encroachment increases, prompting the manufacturer to reduce abatement inputs and unit abatement levels. Elevated encroachment costs do not foster demand growth and may even lead to a decline in demand. In such cases, the manufacturer needs to implement only a lower level of abatement per unit to meet the expected abatement requirements. Furthermore, when the retailer has made low-carbon investments, the unit abatement level after channel encroachment is likely to exceed that before encroachment. This result primarily stems from the market expansion driven by low-carbon investment, which compels the manufacturer to adopt more robust abatement measures to control overall carbon emissions.

Proposition 2. The optimal wholesale price and selling price before and after manufacturer encroachment satisfy the following relationships, respectively:

- (1) $w^{NE^*} < w^{NN^*}$ and $p_r^{NE^*} < p_r^{NN^*}$ if $c < c_1$; otherwise, $w^{NE^*} > w^{NN^*}$, and $p_r^{NE^*} > p_r^{NN^*}$;
- (2) $w^{LE^*} < w^{LN^*}$, and $p_r^{LE^*} < p_r^{LN^*}$ if $c < c_2$; otherwise, $w^{LE^*} > w^{LN^*}$, and $p_r^{LE^*} > p_r^{LN^*}$.

Proposition 2 highlights the impact of manufacturer channel encroachment actions on wholesale prices and retail channel sales prices. When the unit encroachment cost remains below a certain threshold, the retailer can benefit from a lower wholesale price resulting from the manufacturer's encroachment. This result, in turn, enables consumers to access the product through the

retail channel at a more affordable price. However, if the unit cost of encroachment exceeds the specified threshold, the manufacturer chooses to strategically increase the wholesale price to safeguard the competitive advantage of the direct sales channel. These findings are consistent with studies related to channel encroachment in non-low-carbon contexts, such as Yoon (2016). Nevertheless, this study also reveals that the extent to which encroachment affects product prices is influenced by various factors, including the initial level of unit carbon emissions and the effects of the retailer's low-carbon investment. For instance, a high initial level of unit carbon emissions increases the likelihood of the manufacturer setting higher wholesale prices after encroachment.

Proposition 3. The optimal profits of the two firms before and after manufacturer encroachment satisfy the following relationships:

- (1) $\pi_r^{NE^*} < \pi_r^{NN^*}$ if $c < c_1$; otherwise, $\pi_r^{NE^*} > \pi_r^{NN^*}$;
- (2) $\pi_m^{NE^*} > \pi_m^{NN^*}$; (3) $\pi_r^{LE^*} < \pi_r^{LN^*}$ if $c < c_2$; otherwise, $\pi_r^{LE^*} > \pi_r^{LN^*}$; (4) $\pi_m^{LE^*} > \pi_m^{LN^*}$.

Proposition 3 illustrates that the retailer may not necessarily experience a loss in profit due to manufacturer encroachment. However, the manufacturer consistently stands to gain increased profits through such encroachment. Specifically, when the unit cost of encroachment remains relatively low, encroachment leads to reduced profits for the retailer. This result differs from the findings of Li et al. (2021c), who suggested that retailers tend to adopt encroachment strategies when encroachment costs are low. This distinction arises primarily because our study shows that wholesale and retail prices decrease after manufacturer encroachment. As a result, the retailer's marginal profit decreases, reducing its overall profit. Conversely, in scenarios where the unit encroachment cost is high, even though wholesale and retail channel prices increase, the direct selling channel price significantly increases due to the encroachment cost. This result enables the retailer to secure substantial profits through its cost advantage.

Proposition 4. By employing total carbon emissions as a criterion for assessing environmental damage, the environmental damage before and after manufacturer encroachment satisfies the following relationship:

- (1) $E^{NE^*} < E^{NN^*}$ if $c < c_1$; otherwise, $E^{NE^*} > E^{NN^*}$;
- (2) $E^{LE^*} < E^{LN^*}$ if $c < c_3$; otherwise, $E^{LE^*} > E^{LN^*}$. Here, $c_3 = (p_e((2a-ep_e)B_1 + (1-b)m) + 2B_2eh)/(4-2b)p_e$.

Proposition 4 illustrates that when the unit cost of encroachment (c) falls within distinct threshold ranges, a significant difference arises in the total carbon emissions within the supply chain before and after the manufacturer's encroachment. For example, when c is below the relevant threshold, manufacturer encroachment reduces the firm's environmental effect. However, when c surpasses the corresponding threshold, manufacturer encroachment exacerbates environmental harm. Additionally, under retailer low-carbon investment, environmental damage is

more likely to be lower after manufacturer encroachment than before encroachment compared to scenarios without retailer low-carbon investment. The disparity in total emissions across various scenarios primarily depends on the initial level of unit carbon emissions, the unit abatement level, and the demand. On the one hand, in situations where the encroachment cost remains low, manufacturer encroachment simultaneously raises the unit abatement level and increases market demand. If the overall carbon emissions increase because the demand expansion is less than the total emission reductions achieved through the elevated unit abatement level, then the total emissions after encroachment remain lower than those before encroachment. On the other hand, when the encroachment cost is significant, manufacturer encroachment reduces demand and the unit abatement level. If the decrease in total emissions resulting from reduced demand is less than the loss experienced in total emission reductions due to the decrease in the unit abatement level, then manufacturer encroachment leads to more significant environmental damage than does a scenario without encroachment.

5.2 Impact of retailer’s low-carbon investment

This section examines the influence of retailers’ low-carbon investment on equilibrium strategies and corporate profits in the absence and presence of manufacturer encroachment.

Proposition 5. The optimal unit abatement level before and after the low-carbon investment of the retailer satisfies the following: $x^{LN^*} > x^{NN^*}$ and $x^{LE^*} > x^{NE^*}$, respectively.

Proposition 5 suggests that, irrespective of whether channel encroachment occurs, the retailer’s low-carbon investment can lead to an increase in the unit abatement level. This result primarily results from the effect of low-carbon investment, which stimulates market demand. Consequently, manufacturers are compelled to establish ambitious unit abatement targets to comply with government-imposed carbon emission restrictions. This proposition highlights the retailer’s capacity to effectively incentivize manufacturers to mitigate carbon emissions by leveraging its own investments. Whether it pertains to a single retail channel or involves channel encroachment, retailer investment serves as a potent incentive for abatement. Therefore, this proposition introduces a novel and operationally feasible approach for retailers, particularly those emphasizing low-carbon practices, to reduce emissions from supply chain production.

Proposition 6. The optimal wholesale and retail prices before and after the low-carbon investment of the retailer satisfy the following relations, respectively:

- (1) $w^{LN^*} < w^{NN^*}$ if $h < \frac{p_e^2}{2}$; otherwise, $w^{LN^*} > w^{NN^*}$;
- (2) $w^{LE^*} < w^{NE^*}$ if $h < \frac{(4-3b)p_e^2}{(4-2b^2)}$; otherwise, $w^{LE^*} > w^{NE^*}$;

(3) $p_r^{LN^*} < p_r^{NN^*}$ if $h < \frac{p_e^2}{3}$; otherwise, $p_r^{LN^*} > p_r^{NN^*}$;

(4) $p_d^{LE^*} < p_d^{NE^*}$; $p_r^{LE^*} < p_r^{NE^*}$ if $h < \frac{(5-3b)p_e^2}{(6-2b^2)}$; otherwise, $p_r^{LE^*} > p_r^{NE^*}$.

Propositions 6 (1) and (2) lead to the conclusion that, regardless of the presence or absence of channel encroachment, the retailer can only secure reduced wholesale prices following low-carbon investments when the abatement cost coefficients fall below the corresponding thresholds. This observation implies that the manufacturer’s pricing strategy is contingent primarily on the cost situation, making it challenging for low-carbon investments to substantially affect wholesale prices. This phenomenon also explains why upstream manufacturers often refrain from providing price concessions as incentives when retailers make low-carbon investments. For example, BMWs opt to provide low-carbon certification to qualifying retailers instead of offering financial incentives. Furthermore, in scenarios involving manufacturer encroachment, the level of competition between the two channels directly influences the threshold at which the manufacturer can lower wholesale prices. Higher competition between the two channels results in a higher threshold for the manufacturer to lower wholesale prices. This finding indirectly highlights the manufacturer’s increasing sensitivity to the retail channel after encroachment and its use of price strategies to enhance the competitiveness of its direct sales channel by suppressing the retail channel.

Propositions 6 (3) and (4) reveal that when the abatement cost coefficient falls below the corresponding threshold, the retailer with low-carbon investment sets a lower retail price than when there is no low-carbon investment. This phenomenon is primarily attributed to the decline in wholesale prices, which prompts the retailer to adjust its retail prices accordingly. Furthermore, in the context of a retailer with low-carbon investment, the manufacturer chooses to reduce the price within the direct selling channel following encroachment. This strategic decision arises primarily because of the favorable effect of low-carbon investment on the retail channel. Consequently, the manufacturer chooses to mitigate this advantage by lowering the price within the direct selling channel.

Proposition 7. The optimal profits of the two companies before and after the low-carbon investment of the retailer satisfy the following relations:

(1) $\pi_m^{LN^*} > \pi_m^{NN^*}$; (2) $\pi_r^{LN^*} > \pi_r^{NN^*}$ if $F < \frac{h^2m(2a+m-2ep_e)}{(-4h+p_e^2)^2}$;

otherwise, $\pi_r^{LN^*} < \pi_r^{NN^*}$; (3) $\pi_m^{LE^*} > \pi_m^{NE^*}$; (4) $\pi_r^{LE^*} > \pi_r^{NE^*}$ if

$$F < \frac{\left([2h(a(-1+b)-bc-m)-2(-1+b)ehp_e+(c+m)p_e^2]^2 \right)}{\left([-2a(-1+b)h-2bch-2(-1+b)ehp_e+cp_e^2]^2 \right)} ;$$

otherwise, $\pi_r^{LE^*} < \pi_r^{NE^*}$.

Proposition 7 underscores that the manufacturer can

benefit from the retailer’s low-carbon investment, regardless of the presence or absence of channel encroachment. This phenomenon primarily arises from investments stimulating demand within the retail channel, leading to increased wholesale profits for the manufacturer. Consequently, the low-carbon investments of the retailer consistently yield favorable results for manufacturers. However, if the cost associated with low-carbon investment remains below a specific threshold, the retailer can realize higher profits from such investments than in scenarios without low-carbon investment. This discovery also indirectly sheds light on the strategies of prominent retailers such as Carrefour and Lidl, who invest in low-carbon stores in accordance with their specific situations.

Proposition 8. With total carbon emissions employed as a metric for assessing environmental damage, the environmental effects with and without retailer low-carbon investments adhere to the following relationships:

(1) $E^{LN^*} < E^{NN^*}$

if

$$h < \frac{((2a + m)p_e - ep_e^2)}{(4e)};$$

otherwise, $E^{LN^*} > E^{NN^*}$;

(2) $E^{LE^*} < E^{NE^*}$

if

$$h < \frac{p_e[(2a - ep_e)(3 - 2b) + m(1 - b) - 2(2 - b)]}{2(2 - b^2)e};$$

otherwise, $E^{LE^*} > E^{NE^*}$.

Proposition 8 highlights that when assessing total carbon emissions as a metric, the retailer’s low-carbon investment may not necessarily lead to an improvement in the environmental effect of the supply chain. This observation primarily arises from the low-carbon investment stimulating demand within retail channels, which may contribute to increased total carbon emissions. Specifically, when the abatement cost coefficient remains low, regardless of whether manufacturer encroachment occurs, the total carbon emissions under low-carbon investment are consistently lower than those without such

investment. However, if the cost coefficient surpasses a specific threshold, then the retailer’s low-carbon investment exacerbates the environmental effect of the supply chain. This result occurs because the manufacturer reduces the unit abatement level with high cost coefficients, while the low-carbon investment of the retailer amplifies market demand, leading to an increase in carbon emissions. Consequently, such investment exacerbates the carbon emission issue in this context.

6 Numerical analyses

In this section, numerical examples are used to explore the effects of carbon prices on the abatement level and the profit of firms. Referring to Zhou et al. (2020), the parameters are set as follows: $a = 350$, $e = 30$, $G = 4000$, $h = 100$, $c = 5$, $m = 60$, $F = 800$, $p_e \in [0, 10]$ and $b = 0.5$.

Figure 1 illustrates that the optimal unit abatement level initially increases and subsequently decreases with increasing carbon credit prices. This trend also provides a basis for government regulation of enterprise abatement levels through carbon pricing. However, this conclusion differs from the findings of Wang et al. (2020), who argue that the unit carbon reduction level is negatively correlated with carbon prices. As the unit reduction level increases, the manufacturer’s abatement costs may significantly increase. In such a scenario, rational manufacturers may choose to reduce production to lower the requirements for carbon abatement levels.

Furthermore, when the unit encroachment cost is high, the unit abatement level after encroachment is lower than that before encroachment. The low-carbon investments of the retailer can increase the level of unit abatement, regardless of whether manufacturer encroachment occurs. As the price of carbon credits rises, the gap between the unit abatement levels in the LE and NE models and in the LN and NN models widens. This finding demonstrates that a high price of carbon credits makes the effect of the retailer’s low-carbon investment on abatement more pronounced.

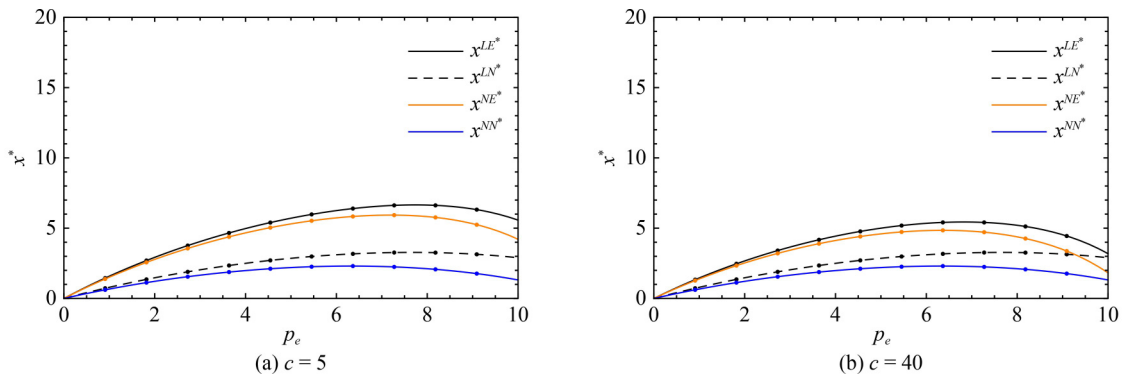


Fig. 1 Effect of carbon prices on the unit abatement level.

As depicted in Fig. 2, a clear negative correlation exists between the retailer’s optimal profit and the carbon price across all the models. Additionally, the effect of the retailer’s low-carbon investment on its profitability is contingent upon the cost of such investment (F). When it is at a high level (e.g., $F = 1600$), the retailer gains greater profits from its low-carbon investment than from its noninvestment if the carbon price falls below the relevant threshold. Conversely, if the carbon price exceeds the corresponding threshold, the retailer will suffer a loss in profit from low-carbon investment. Therefore, if a retailer seeks to boost its profits through low-carbon investments, investing when the carbon price is low will be advantageous.

As illustrated in Fig. 3, when the emission quota is set at a low level, the manufacturer’s profit declines as the carbon price increases. Conversely, when the emission quota is high, the manufacturer’s profit increases with the increase in the carbon price overall. This observation contrasts with the findings of Wang and Wu (2021), who concluded that the manufacturer’s profit diminishes as the carbon price increases. On the one hand, a low emission quota leads to stricter emission regulations being faced by the manufacturer. In this scenario, as the price of carbon credits increases, the manufacturer will need to allocate additional resources toward abatement or the acquisition of carbon credits, thus directly reducing the manufa-

cturer’s profit. On the other hand, when the emission quota is low, the manufacturer may moderately increase product prices and reduce production volume due to cost pressures, which will further reduce the manufacturer’s sales profit. Similarly, when the emission quota is set at a high level, the manufacturer can effectively achieve the overarching abatement objective while incurring lower costs. Therefore, as the carbon price increases, the manufacturer can obtain increased carbon trading income, resulting in an overall upward trend in total profit.

7 Extension

This section aims to substantiate the robustness of the relevant conclusions by considering the endogeneity of parameter m . To reduce the workload, this section discusses only the more complex LE mode as an example. For the sake of differentiation from the preceding analyses, the LE mode under the endogenous parameter m is designated the $LE2$ mode.

In the $LE2$ model, the manufacturer implements channel encroachment, and the retailer has a low-carbon investment. The demand functions for the retail channel and direct sales channel are $p_r^{LE2} = a + m - q_r - bq_d$ and $p_d^{LE2} = a - q_d - bq_r$, respectively. In addition, the total cost of low-carbon investment is divided into two components,

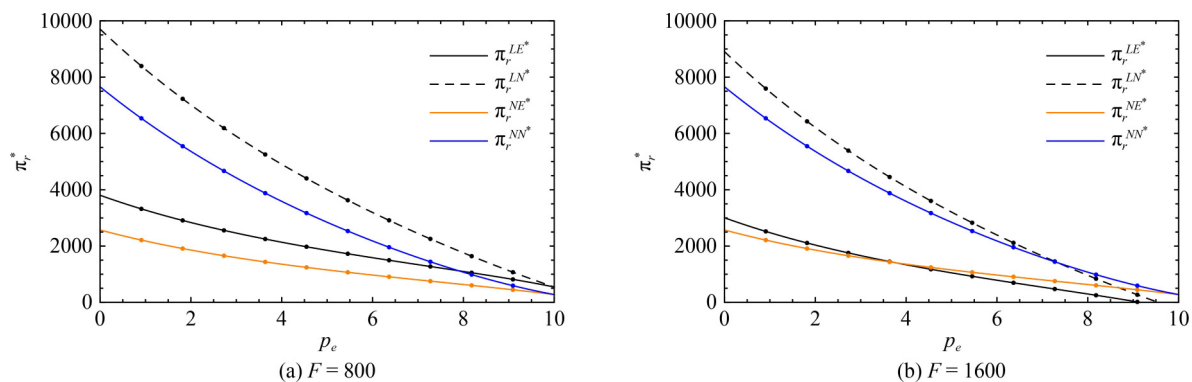


Fig. 2 Effect of carbon prices on retailer profits.

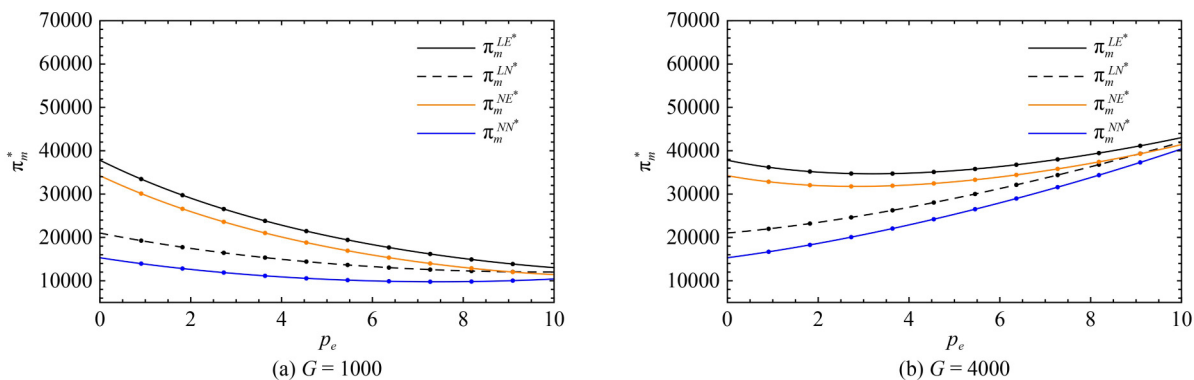


Fig. 3 Effect of carbon prices on manufacturer profits.

namely, fixed and variable (i.e., $F + \frac{km^2}{2}$). At this time, F represents fixed costs, such as the clean energy and equipment procurement costs. Referring to Yang et al. (2021) and Xia and Niu (2021), this section formulates the retailer's variable cost associated with low-carbon investment as a quadratic function linked to parameter m . This form of cost function can efficiently capture the diminishing marginal returns characteristic of the retailer's low-carbon investments. The optimal profit functions for the two firms are $\pi_m^{LE2} = (p_d^{LE2} - c)q_d + wq_r - p_e(e - x)(q_r + q_d) + p_eG - hx^2/2$ and $\pi_r^{LE2} = (p_r^{LE2} - w)q_r - (F + km^2/2)$.

Acknowledging the challenge of directly analyzing equilibrium strategies within the $LE2$ mode, this section will employ numerical examples. These examples will facilitate a comparison of the changing trends in unit abatement levels and corporate profits between the LE mode and the $LE2$ mode. This analysis will demonstrate the robustness of the primary research conclusions even in cases where parameter m is treated as endogenous. The main parameters in this section take the same values as in the previous section, where $F = 800$ and $k = 90$. This paper presents the equalization strategy of the $LE2$ mode in the appendix.

In conjunction with Figs. 4–6, it is evident that the unit abatement levels and corporate profits are higher within the LE model than within the $LE2$ model. This outcome is largely due to the $LE2$ model taking into account the

fixed and variable costs of low-carbon investments. The optimal unit abatement level, manufacturer's profit, and retailer's profit exhibit strong consistency between the scenarios of endogenous and exogenous parameter adjustments m . This outcome also shows that the insights we obtained when m is exogenous still hold when m is endogenous. Hence, the core findings of this study remain robust.

8 Conclusions and implications

With respect to a low-carbon supply chain subject to a C&T mechanism, this study formulates a series of game models that include four scenarios: manufacturer involvement or noninvolvement in encroachment and retailer decisions regarding low-carbon investment or noninvestment. The primary focus of this study lies in analyzing manufacturers' encroachment and abatement strategies, retailers' choices concerning low-carbon investment, and the pricing strategies adopted within the supply chain. Furthermore, this study conducts a thorough examination of the effect of various factors through numerical examples and validates the steadfastness of the central conclusions. The principal findings and managerial implications are summarized below.

First, there exists a negative correlation between the unit carbon reduction level and the initial carbon emission

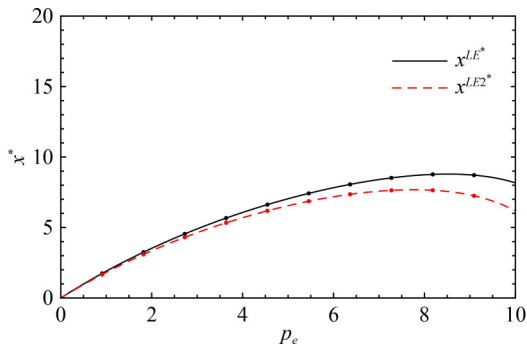


Fig. 4 Effect of carbon prices on the unit abatement level.

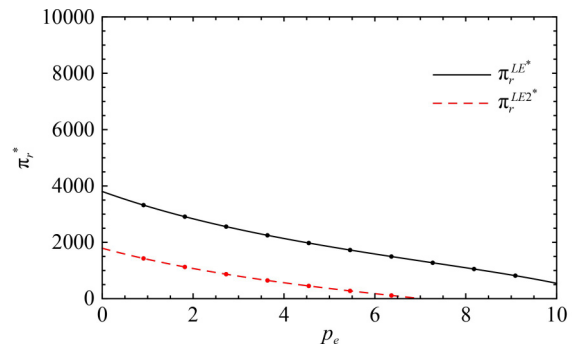


Fig. 5 Effect of carbon prices on retailer profits.

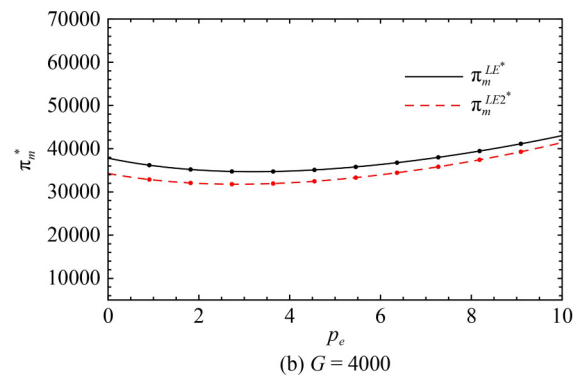
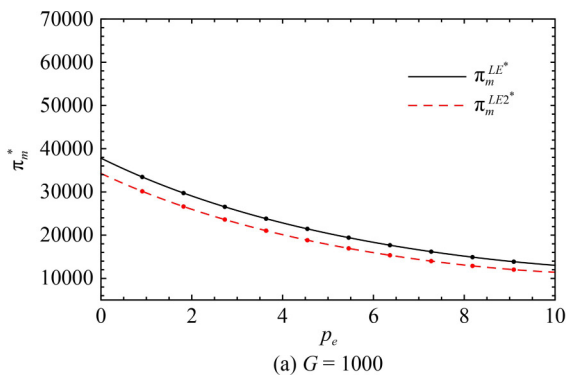


Fig. 6 Effect of carbon credit prices on manufacturer profits.

level. A high initial emission level leads to a decrease in demand and profits for members of the supply chain. In simpler terms, firms with high initial emissions not only encounter challenges in realizing their abatement potential under C&T mechanisms but also engender profit losses for fellow supply chain entities.

Second, if the unit encroachment costs do not surpass the corresponding threshold, encroachment enhances the unit reduction level while simultaneously reducing wholesale prices and retailer profits. However, it is important to note that the manufacturer consistently benefits from encroachment. Furthermore, when the unit cost of encroachment level falls below a specific threshold, the environmental damage postencroachment is lower than that in the preencroachment scenario.

Third, in comparison to scenarios devoid of low-carbon investment, the manufacturer should set a higher unit abatement level and a lower direct selling price when the retailer opts for low-carbon investments. Additionally, irrespective of the presence of channel encroachment, the manufacturer consistently leans toward offering a lower wholesale price to retailers engaged in low-carbon investments if the abatement cost coefficient is lower than the corresponding threshold.

Fourth, the retailer's engagement in low-carbon investment consistently yields advantages for the manufacturer. Furthermore, the retailer is likely to increase its profits through the implementation of low-carbon investments, particularly when the carbon price is low. The impact of the retailer's low-carbon investment in reducing environmental damage is significant only when the abatement cost coefficient is at a low level. However, in situations where the retailer has already made low-carbon investments, the likelihood of a decrease in environmental damage following channel encroachment is greater than that prior to such encroachment.

Finally, retailer profits exhibit a consistent negative correlation with carbon prices, with higher carbon prices enhancing the incentivizing effect of retailer low-carbon investment on manufacturer abatement. Nevertheless, in cases characterized by relatively lax carbon emission quota constraints, the manufacturer's optimal profit can increase with the price of carbon credits. Furthermore, this study investigates a scenario in which the level of demand expansion in retail channels is endogenous, and the results affirm the robustness of the principal findings in this study.

Based on the aforementioned findings, this study elucidates the following managerial insights:

(1) Policymakers should formulate adaptable abatement progress plans for entities with elevated initial carbon emission levels, thereby mitigating the policy's impact on the entire supply chain system. It is crucial to maintain the carbon trading price within a reasonable range while ensuring a modest upward trajectory. Furthermore,

policymakers should impose constraints on the occurrence of high-cost encroachment behaviors within emission-dependent industries, as such encroachment costs may diminish firms' incentives for abatement investment.

(2) Manufacturers should carefully assess initial unit-level of carbon emissions, the carbon credit trading price, and encroachment costs when contemplating engagement in encroachment. These factors significantly influence channel demand and the retailer's postencroachment profitability. From a profit-maximizing standpoint, manufacturers should contemplate the development of direct sales channels. Additionally, in situations where encroachment costs are substantial, retailers are more inclined to accept manufacturer encroachment.

(3) Retailers should be cognizant that low-carbon investments may not invariably yield high returns. Nonetheless, executing such investments during periods of low carbon prices is likely to yield substantial profits. For retailers striving to enhance the environmental sustainability of their supply chain, low-carbon investments serve as an effective tool for incentivizing manufacturers to reduce emissions and curtail environmental damage, irrespective of manufacturer encroachment. Furthermore, these investments contribute to reducing environmental harm throughout the entire supply chain. However, retailers should diligently manage the costs associated with low-carbon investments to establish mutually beneficial arrangements with manufacturers.

(4) Recognizing that manufacturers stand to benefit from channel encroachment and retailer low-carbon investments, they may consider sharing a portion of the revenue with the retailer postencroachment or sharing part of the retailer's low-carbon investment costs. Additionally, consumers' level of environmental awareness significantly influences retailers' decisions regarding low-carbon investments and manufacturers' choices concerning emission reduction. Hence, consumers are encouraged to prioritize the purchase of low-carbon products that align with their capacities and capabilities.

While this study has yielded valuable research results, it is not devoid of limitations. First, it assumes that retailer low-carbon investments can expand demand in the retail channel but overlooks the potential spillover effects of such investments. Future research should consider these factors for a more refined analysis. Furthermore, the study's conclusions are contingent upon the assumption of information symmetry. Subsequent investigations could investigate the interplay between retailer investment strategies and manufacturer encroachment strategies within the framework of asymmetric information.

Competing Interests The authors declare that they have no competing interests.

Appendix A

Lemmas 1–4 can be proven in a similar way. Given that the proof of Lemma 4 is the most complicated, we provide only the detailed proof procedure of Lemma 4 here.

Proof of Lemma 4

Backward induction is used to solve the theorem. Solving the first- and second-order partial derivatives of π_r^{LE} with respect to q_r , we have $\frac{\partial \pi_r^{LE}}{\partial q_r} = a + m - w - bq_d - 2q_r$ and $\frac{\partial^2 \pi_r^{LE}}{\partial q_r^2} = -2 < 0$, respectively. By setting $\frac{\partial \pi_r^{LE}}{\partial q_r} = 0$, we obtain $q_r(x, w, q_d) = \frac{1}{2}(a + m - w - bq_d)$. Substituting $q_r(x, w, q_d)$ into π_m^{LE} , we can obtain the Hessian matrix

$$\frac{\partial^2 \pi_m^{LE}}{\partial x^2} = \frac{-2(-2 + b^2)hx + (a(-3 + 2b) - (-2 + b)c + (-1 + b)m)p_e + (-3 + 2b)(-e + x)p_e^2}{2(-2 + b^2)}.$$

Thus, if $h > \frac{p_e^2(-3 + 2b)}{2(-2 + b^2)}$, then $\frac{\partial^2 \pi_m^{LE}}{\partial x^2} < 0$. At this time, $\frac{\partial \pi_m^{LE}}{\partial x} = 0$, and $x^{LE^*} = \frac{p_e[a(3 - 2b) + (-2 + b)c + m - bm + (-3 + 2b)ep_e]}{-2(-2 + b^2)h + (-3 + 2b)p_e^2}$. We can obtain the optimal unit abatement level $x^{LE^*} = \frac{p_e[a(3 - 2b) + (-2 + b)c + m - bm + (-3 + 2b)ep_e]}{-2(-2 + b^2)h + (-3 + 2b)p_e^2}$. Finally, substituting x^{LE^*} into $w(x)$, $q_d(x)$, and $q_r(x)$, we can obtain x^{LE^*} , w^{LE^*} , $q_d^{LE^*}$, and $q_r^{LE^*}$, respectively. Using these equilibrium solutions, we can obtain $\pi_s^{MG^*}$, $\pi_m^{MG^*}$, and CS^{MG^*} .

Proof of Corollary 1

For ease of presentation, we let $A_1 = a(3 - 2b) + (-2 + b)c + m - bm + (-3 + 2b)ep_e > 0$. Taking the LE model as an example, Corollary 1 can be proven by taking the first-order derivatives of each equilibrium strategy and the firm's profit with respect to h . The conclusions under the NN, NE, and LN models can also be obtained in the same way.

$$(1) \frac{\partial x^{LE^*}}{\partial h} = \frac{2(-2 + b^2)p_e A_1}{[2(-2 + b^2)h + (3 - 2b)p_e^2]^2} < 0.$$

$$(2) \frac{\partial w^{LE^*}}{\partial h} = -\frac{(-2 + b^2)p_e^2 A_1}{[2(-2 + b^2)h + (3 - 2b)p_e^2]^2} > 0,$$

$H(w, q_d) = \begin{pmatrix} -1 & 0 \\ 0 & -2 + b^2 \end{pmatrix}$. Given that $|H(w, q_d)| = 2 - b^2 > 0$ and $-1 < 0$, π_m^{LE} is jointly concave in w and q_d . According to $\frac{\partial \pi_m^{LE}}{\partial w} = \frac{\partial \pi_m^{LE}}{\partial q_d} = 0$, we have $w(x) = \frac{1}{2}(a + m + (e - x)p_e)$ and $q_d(x) = \frac{a(-2 + b) + 2c + bm - (-2 + b)(e - x)p_e}{2(-2 + b^2)}$. Substituting $w(x)$ and $q_d(x)$ into $q_r(x, w, p_d)$, we obtain $q_r(x) = -\frac{a - ab + bc + m + (-1 + b)(e - x)p_e}{2(-2 + b^2)}$. Subsequently, substituting $w(x)$, $q_d(x)$, and $q_r(x)$ into π_m^{LE} , we obtain $\frac{\partial^2 \pi_m^{LE}}{\partial x^2} = -h + \frac{(-3 + 2b)p_e^2}{2(-2 + b^2)}$ and

$$\frac{\partial p_r^{LE^*}}{\partial h} = -\frac{[-1 + (-1 + b)b]p_e^2 A_1}{[2(-2 + b^2)h + (3 - 2b)p_e^2]^2} > 0.$$

$$(3) \frac{\partial \pi_m^{LE^*}}{\partial h} = -\frac{p_e^2 A_1}{2[2(-2 + b^2)h + (3 - 2b)p_e^2]^2} < 0, \quad \frac{\partial \pi_r^{LE^*}}{\partial h} = \frac{(-1 + b)p_e^2 A_1 [2h(a - ab + bc + m) + 2(-1 + b)ehp_e - (c + m)p_e^2]}{[2(-2 + b^2)h + (3 - 2b)p_e^2]^3}.$$

According to $q_r^{LE^*} > 0$, we can obtain $2h(a - ab + bc + m) + 2(-1 + b)ehp_e - (c + m)p_e^2 > 0$. Moreover, $2(-2 + b^2)h + (3 - 2b)p_e^2 < 0$. Thus, $\frac{\partial \pi_r^{LE^*}}{\partial h} < 0$.

Proof of Corollary 2

Taking the LE model as an example, Corollary 1 can be proven by taking the first-order derivatives of each equilibrium strategy with respect to e . In addition, the conclusions under the NN, NE, and LN models can be obtained in the same way.

$$(1) \frac{\partial x^{LE^*}}{\partial e} = \frac{(3 - 2b)p_e^2}{2(-2 + b^2)h + (3 - 2b)p_e^2} < 0.$$

$$(2) \frac{\partial w^{LE^*}}{\partial e} = \frac{(-2 + b^2)hp_e}{2(-2 + b^2)h + (3 - 2b)p_e^2} > 0,$$

$$\frac{\partial p_d^{LE^*}}{\partial e} = \frac{(-2 + b^2)hp_e}{2(-2 + b^2)h + (3 - 2b)p_e^2} > 0,$$

$$\frac{\partial p_r^{LE^*}}{\partial e} = \frac{[-1 + (-1 + b)b]hp_e}{2(-2 + b^2)h + (3 - 2b)p_e^2} > 0.$$

$$(3) \frac{\partial \pi_m^{LE^*}}{\partial e} = \frac{hp_e[a(3 - 2b) + (-2 + b)c + m - bm + (-3 + 2b)ep_e]}{2(-2 + b^2)h + (3 - 2b)p_e^2} < 0,$$

$$\frac{\partial \pi_r^{LE^*}}{\partial e} = \frac{(-1+b)hp_e [2h(a-ab+bc+m) + 2(-1+b)hep_e - (c+m)]p_e^2}{[2(-2+b^2)h + (3-2b)p_e^2]^2} < 0.$$

Proof of Proposition 1

$$(1) x^{NE^*} - x^{NN^*} = \frac{(-2+b)p_e [-2(a(-2+b) + 2c)h + 2(-2+b)hep_e + cp_e^2]}{(4h - p_e^2)[2(-2+b^2)h + (3-2b)p_e^2]}.$$

Given that $2(-2+b^2)h + (3-2b)p_e^2 < 0$, if $-2(a(-2+b) + 2c)h + 2(-2+b)hep_e + cp_e^2 > 0$, then $x^{NE^*} > x^{NN^*}$. Thus,

$$\text{when } c < \frac{2h[(a-ep_e)(2-b) - bm] + mp_e^2}{4h - p_e^2}, x^{NE^*} > x^{NN^*}.$$

$$(2) x^{LE^*} - x^{LN^*} = \frac{(-2+b)p_e [-2h(a(-2+b) + 2c + bm) + 2(-2+b)hep_e + (c+m)p_e^2]}{(4h - p_e^2)[2(-2+b^2)h + (3-2b)p_e^2]}.$$

Given that $2(-2+b^2)h + (3-2b)p_e^2 < 0$, if $-2h[a(-2+b) + 2c + bm] + 2(-2+b)hep_e + (c+m)p_e^2 > 0$, then $x^{LE^*} > x^{LN^*}$.

Thus, when $c < \frac{-2h[a(-2+b) + bm] + 2(-2+b)hep_e + mp_e^2}{4h - p_e^2}$, $x^{LE^*} > x^{LN^*}$.

Proof of Proposition 2

The proof of Proposition 2 is similar to that of Proposition 1. Thus, we omit it here.

Proof of Proposition 3

$$(1) \pi_r^{NE^*} - \pi_r^{NN^*} = -\frac{h^2(a-ep_e)^2}{(-4h + p_e^2)^2} + \frac{[2a(-1+b)h - 2bch - 2(-1+b)hep_e + cp_e^2]^2}{4[2(-2+b^2)h + (3-2b)p_e^2]^2}.$$

The sign of $\pi_r^{NE^*} - \pi_r^{NN^*}$ is determined by the sign of $f(c) = -4h^2(a-ep_e)^2[2(-2+b^2)h + (3-2b)p_e^2]^2 + (-4h + p_e^2)^2 [2a(-1+b)h - 2bch - 2(-1+b)hep_e + cp_e^2]^2$. By solving $f(c) = 0$, we can obtain $c_1 = \frac{2h(2-b)(a-ep_e)}{4h - p_e^2}$ and $c_3 = \frac{2h(a-ep_e)[2h(4-b(2+b)) - (4-3b)p_e^2]}{8bh^2 - 2(2+b)hp_e^2 + p_e^4}$. According to

$$\frac{\partial c_3}{\partial b} = \frac{2h(a-ep_e)[4(4+b^2)h^2 - 4(3+b)hp_e^2 + 3p_e^4]}{(4h - p_e^2)(-2bh + p_e^2)^2} > 0,$$

$\max\{c_3\} = -\frac{2h(a-ep_e)}{4h - p_e^2}$ when $b = 1$. Therefore $c_3 < 0$. In summary, if $c < c_1$, then $f(c) < 0$, and $\pi_r^{NE^*} < \pi_r^{NN^*}$; if $c > c_1$, then $f(c) > 0$, and $\pi_r^{NE^*} > \pi_r^{NN^*}$.

$$(2) \pi_m^{NE^*} - \pi_m^{NN^*} = \frac{h(-a(-2+b) + 2c)^2 h + p_e(2(-2+b)[a(-2+b) + 2c]eh + p_e[a(-2+b)c + c^2 - (-2+b)^2 e^2 h - (-2+b)cep_e])}{(4h - p_e^2)[2(-2+b^2)h + (3-2b)p_e^2]}.$$

The sign of $\pi_m^{NE^*} - \pi_m^{NN^*}$ is determined by the sign of $g(c) = -[a(-2+b) + 2c]^2 h + p_e(2(-2+b)[a(-2+b) + 2c]eh + p_e[a(-2+b)c + c^2 - (-2+b)^2 e^2 h - (-2+b)cep_e])$. Given

that $(-2+b)^2 p_e^2 (a-ep_e)^2 (-4h + p_e^2) < 0$, $g(c) = 0$ has no real roots. Thus, $g(c) < 0$. Considering $(4h - p_e^2)[2(-2+b^2)h + (3-2b)p_e^2] < 0$, we have $\pi_m^{NE^*} > \pi_m^{NN^*}$.

$$(3) \pi_r^{LE^*} - \pi_r^{LN^*} = -\frac{h^2(a+m-ep_e)^2}{(-4h + p_e^2)^2} + \frac{[2h(a(-1+b) - bc - m) - 2(-1+b)hep_e + (c+m)p_e^2]^2}{4[2(-2+b^2)h + (3-2b)p_e^2]^2}.$$

The sign of $\pi_r^{LE^*} - \pi_r^{LN^*}$ is determined by the sign of $f_2(c) = -4h^2(a+m-ep_e)^2(2(-2+b^2)h + (3-2b)p_e^2) + (-4h + p_e^2)^2 (2h[a(-1+b) - bc - m] - 2(-1+b)hep_e + (c+m)p_e^2)^2$. That is, if $f_2(c) > 0$, then $\pi_r^{LE^*} > \pi_r^{LN^*}$; if $f_2(c) < 0$, then $\pi_r^{LE^*} < \pi_r^{LN^*}$. If $f_2(c) = 0$, we can obtain the roots $c_2 = \frac{2h[(a-ep_e)(2-b) - bm] + mp_e^2}{4h - p_e^2} > 0$ and $c_4 = -m +$

$$\frac{2(-2+b)h(a+m-ep_e)}{4h - p_e^2} + \frac{4(-1+b)h(a+m-ep_e)}{2bh - p_e^2}.$$

According to $\frac{\partial c_4}{\partial b} = \frac{2h(a+m-ep_e)[4(4+b^2)h^2 - 4(3+b)hp_e^2 + 3p_e^4]}{(4h - p_e^2)(-2bh + p_e^2)^2} > 0$, we have $\max\{c_4\} = -m + \frac{-2h(a+m-ep_e)}{4h - p_e^2} < 0$, $c_4 < 0$. Thus,

if $c < c_2$, then $f_2(c) < 0$, $\pi_r^{LE^*} < \pi_r^{LN^*}$; if $c > c_2$, then $f_2(c) > 0$, $\pi_r^{LE^*} > \pi_r^{LN^*}$.

$$(4) \pi_m^{LE^*} - \pi_m^{LN^*} = -\frac{[-2h(a(-2+b)+2c+bm)+2(-2+b)ehp_e+(c+m)p_e^2]^2}{4(4h-p_e^2)[2(-2+b^2)h+(3-2b)p_e^2]} > 0.$$

Proof of Proposition 4

$$(1) E^{NE^*} - E^{NN^*} = (e - x^{NE^*})(q_r^{NE^*} + q_d^{NE^*}) - (e - x^{NN^*})(q_r^{NN^*}).$$

$$E^{NE^*} - E^{NN^*} = \frac{h(ap_e - 4eh)(a - ep_e)}{(4h + p_e^2)} - \frac{h(2(-2+b^2)eh + (a(3-2b) + (-2+b)c)p_e)(a(3-2b) + (-2+b)c - (3-2b)ep_e)}{(2(-2+b^2)h + (3-2b)p_e^2)^2}.$$

According to $2(-2+b^2)h + (3-2b)p_e^2 < 0$, we can obtain $\frac{\partial^2(E^{NE^*} - E^{NN^*})}{\partial(c)^2} = -\frac{2(-2+b^2)hp_e}{(2(-2+b^2)h + (3-2b)p_e^2)^2} < 0$ and $(E^{NE^*} - E^{NN^*})|_{c=0} = h(a - ep_e) \left(\frac{ap_e - 4eh}{(p_e^2 - 4h)^2} + \frac{(-3+2b)(2(-2+b^2)eh + a(3-2b)p_e)}{(2(-2+b^2)h + (3-2b)p_e^2)^2} \right) > 0$. By solving equation $E^{NE^*} - E^{NN^*} = 0$ with respect to c , we can obtain the only nonnegative solution $\frac{2h(2-b)(a-ep_e)}{4h-p_e^2} = c_1$. Thus, if $c < c_1$, then $E^{NE^*} - E^{NN^*} > 0$; if $c > c_1$, then $E^{NE^*} - E^{NN^*} < 0$.

(2) The proof process is the same as that for Proposition

$$4(1), \quad \text{where} \quad E^{LE^*} - E^{LN^*} = \frac{\left(\frac{h(a+m-ep_e)}{(-4h+p_e^2)^2} + \frac{h(-a(3-2b) - (-2+b)c + (-1+b)m + a(3-2b)ep_e)}{(2(-2+b^2)eh + (a(3-2b) + (-2+b)c + m - bm)p_e)} \right)}{(2(-2+b^2)h + a(3-2b)p_e^2)^2}$$

$$\text{and} \quad \frac{\partial^2(E^{LE^*} - E^{LN^*})}{\partial c^2} = -\frac{2(-2+b^2)hp_e}{(2(-2+b^2)h + (3-2b)p_e^2)^2} < 0.$$

By solving equation $E^{LE^*} - E^{LN^*} = 0$ with respect to c , we obtain the only nonnegative solution $\frac{p_e((2a-ep_e)(3-2b) + (1-b)m) - 2(2-b^2)eh}{2(2-b)p_e} = c_5$. Thus, if $c < c_5$, then $E^{LE^*} - E^{LN^*} > 0$; if $c > c_5$, then $E^{LE^*} - E^{LN^*} < 0$.

Proof of Proposition 5

The proof of Proposition 5 is similar to that of

That is,

Proposition 4. Thus, we omit it here.

Proof of Proposition 6

(1) $w^{LN^*} - w^{NN^*} = \frac{m(2h - p_e^2)}{4h - p_e^2}$. Thus, $w^{LN^*} < w^{NN^*}$ when $h < \frac{p_e^2}{2}$.

(2) $w^{LE^*} - w^{NE^*} = \frac{m[2(-2+b^2)h + (4-3b)p_e^2]}{4(-2+b^2)h + (6-4b)p_e^2}$. The sign of $w^{LE^*} - w^{NE^*}$ is determined by the sign of $2(-2+b^2)h + (4-3b)p_e^2$. If $2(-2+b^2)h + (4-3b)p_e^2 = 0$, we have $h(b) = \frac{(4-3b)p_e^2}{2(2-b^2)}$. According to $\frac{\partial h(b)}{\partial b} = \frac{[(8-3b)b-6]p_e^2}{2(-2+b^2)^2} > 0$, we can obtain $\min\{h(b)\} = h(0) = p_e^2 > 0$. Thus, $w^{LE^*} < w^{NE^*}$ when $h < h(b)$.

(3) $p_r^{LN^*} - p_r^{NN^*} = \frac{m(3h - p_e^2)}{4h - p_e^2}$. Thus, $p_r^{LN^*} < p_r^{NN^*}$ when $h < \frac{1}{3}p_e^2$.

(4) $p_r^{LE^*} - p_r^{NE^*} = \frac{m(2(-3+b^2)h + (5-3b)p_e^2)}{4(-2+b^2)h + (6-4b)p_e^2}$. Thus, $p_r^{LE^*} < p_r^{NE^*}$ when $h < \frac{(5-3b)p_e^2}{2(3-b^2)}$. $p_d^{LE^*} - p_d^{NE^*} = \frac{(-1+b)mp_e^2}{4(-2+b^2)h + (6-4b)p_e^2} < 0$.

Proof of Proposition 7

(1) $\pi_m^{LN^*} - \pi_m^{NN^*} = \frac{hm(2a+m-2ep_e)}{8h-2p_e^2} > 0$.

(2) $\pi_r^{LN^*} - \pi_r^{NN^*} = -F + \frac{h^2m(2a+m-2ep_e)}{(-4h+p_e^2)^2}$. Thus, $\pi_r^{LN^*} > \pi_r^{NN^*}$ if $F < \frac{h^2m(2a+m-2ep_e)}{(-4h+p_e^2)^2}$.

(3) $\pi_m^{LE^*} - \pi_m^{NE^*} = \frac{m[-2h(2a(1-b)+2bc+m)+4(1-b)ehp_e+(2c+m)p_e^2]}{4[2(-2+b^2)h+(3-2b)p_e^2]}$. According to $q_r^{LE^*} > 0$, we can obtain $\pi_m^{LE^*} - \pi_m^{NE^*} > 0$.

$$(4) \pi_r^{LE^*} - \pi_r^{NE^*} = -F + \frac{[2h(a(-1+b)-bc-m)-2(-1+b)ehp_e+(c+m)p_e^2]-[2a(-1+b)h-2bch-2(-1+b)ehp_e+cp_e^2]^2}{4[2(-2+b^2)h+(3-2b)p_e^2]^2}.$$

Thus, $\pi_r^{LE^*} > \pi_r^{NE^*}$ if $F < \frac{[2h(-1+b)(a-ep_e) - bc - m] + (c+m)p_e^2 - [2h(-1+b)(a-ep_e) - 2bch + cp_e^2]^2}{4[2(-2+b^2)h + (3-2b)p_e^2]}$.

Proof of Proposition 8

$$(1) \quad E^{LN^*} - E^{NN^*} = (e - x^{LN^*})q_r^{LN^*} - (e - x^{MN^*})q_r^{NN^*} =$$

$\frac{hm[4eh - (2a+m)p_e + ep_e^2]}{(-4h+p_e^2)^2}$. If $h < \frac{(2a+m)p_e - ep_e^2}{4e}$, then $E^{LN^*} < E^{NN^*}$; otherwise, $E^{LN^*} > E^{NN^*}$.

$$(2) \quad E^{LE^*} - E^{NE^*} = \frac{(b-1)hm[2(b^2-2)eh + p_e(a(6-4b) - 2(2-b)c + m - bm - (3-2b)ep_e)]}{[2(-2+b^2)h + (3-2b)p_e^2]}$$

The sign of $E^{LE^*} - E^{NE^*}$ is determined by the sign of $2(b^2-2)eh + p_e(a(6-4b) - 2(2-b)c + m - bm - (3-2b)ep_e)$

Thus, if $h < \frac{p_e[(2a-ep_e)(3-2b) + m(1-b) - 2(2-b)]}{2(2-b^2)e}$, then $h < \frac{p_e[(2a-ep_e)(3-2b) + m(1-b) - 2(2-b)]}{2(2-b^2)e}$,

otherwise, $E^{LE^*} > E^{NE^*}$.

Proof of Extension

The proof is the same as that of Theorem 4. Thus, we omit it here. The specific equilibrium strategy is as follows.

$$x^{LE2^*} = \frac{p_e [c + (-2+b)ck + a(-1+3k-2bk) + e(1+(-3+2b)k)p_e]}{-2h[1+(-2+b^2)k] + [1+(-3+2b)k]p_e^2},$$

$$m^{LE2^*} = \frac{2a(-1+b)h - 2bch - 2(-1+b)ehp_e + cp_e^2}{4h[1+(-2+b^2)k] + [-2+(6-4b)k]p_e^2},$$

$$w^{LE2^*} = \frac{1}{2} \left(a + \frac{p_e [-2eh(1+(-2+b^2)k) + (a+a(-3+2b)k - c(1+(-2+b)k))p_e]}{-2h[1+(-2+b^2)k] + [1+(-3+2b)k]p_e^2} \right),$$

$$q_r^{LE2^*} = \frac{k[2a(-1+b)h - 2bch - 2(-1+b)ehp_e + cp_e^2]}{4h[1+(-2+b^2)k] + [-2+(6-4b)k]p_e^2},$$

$$q_d^{LE2^*} = \frac{2h[a + a(-2+b)k + c(-1+2k)] - 2eh[1+(-2+b)k]p_e - ckp_e^2}{4h[1+(-2+b^2)k] + [-2+(6-4b)k]p_e^2},$$

$$\pi_m^{LE2^*} = \frac{2h[(a-c)^2 + (a^2(-3+2b) - 2a(-2+b)c - 2c^2)k] + p_e(4h(ae(-1+(3-2b)k) + ce(1+(-2+b)k)) + p_e(c^2k + 2e^2h(1-3k+2bk)))}{8h[1+(-2+b^2)k] - 4[1+(-3+2b)k]p_e^2} + Gp_e,$$

$$\pi_r^{LE2^*} = -\frac{1}{8[2h(1+(-2+b^2)k) + (-1+(3-2b)k)p_e^2]} \{4h^2([a(-1+b) - bc]^2(1-2k)k + 8F[1+(-2+b^2)k]^2) + 8(-1+b)(a(-1+b) - bc)eh^2k(-1+2k)p_e - 4h[-c(a-ab+bc) + (-1+b)^2e^2h]k(-1+2k) + 8F(1-3k+2bk)[1+(-2+b^2)k]p_e^2 + 4(-1+b)cehk(-1+2k)p_e^3 + [c^2(1-2k)k + 8F(1-3k+2bk)^2]p_e^4\}.$$

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