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Pricing and Emission Reduction Decisions in a Green Supply Chain: The Roles of Consumer Environmental Awareness, Carbon Tax Policy, and Cooperation Modes

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Abstract

This paper investigates carbon reduction and pricing decisions in a green supply chain composed of a government, a manufacturer, and a retailer, under the joint influence of carbon tax policies and consumer environmental awareness. A game-theoretic framework is developed to systematically compare four cooperation structures: non-cooperation, emission reduction cooperation, pricing cooperation, and full cooperation. The results show that consumer environmental awareness significantly influences firms' green investment, pricing strategies, and the government's carbon tax policy. The analysis further reveals several nonlinear effects under different cooperation modes. In particular, when environmental performance is evaluated in terms of emission intensity, emission-reduction investment improves per-unit environmental performance, although demand expansion under strong consumer environmental awareness may weaken the extent of this improvement. In less environmentally sensitive markets, green investment translates more directly into environmental improvement. Pricing cooperation provides strong incentives for firms to reduce emissions, whereas full cooperation achieves a better balance between environmental and economic performance. This study enriches the theoretical foundation of green supply chain coordination and offers practical insights into carbon tax design and sustainable collaboration strategies.

Keywords: green supply chain; carbon emission reduction; consumer environmental awareness; pricing strategies



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1. Introduction

Global climate change has prompted governments worldwide to adopt carbon reduction policies. Since the 1992 United Nations Framework Convention on Climate Change (UNFCCC), agreements such as the Kyoto Protocol and the Paris Agreement have established binding international goals for greenhouse gas control [1]. Although these agreements have increased the burden of emissions reduction—particularly for developing countries—they have also accelerated the global formulation of carbon policies [2]. By 2021, around 50 countries had achieved carbon peaking, accounting for 36% of global emissions [3]. China, the United States, and the European Union together contribute to over 50% of global emissions. As the largest emitter, China has pledged to reach peak emissions by 2030 and achieve carbon neutrality by 2060 [4], necessitating a nationwide low-carbon transformation and increased investment in green production. In parallel with

policy efforts, consumer environmental awareness has significantly increased. Consumers in both Europe and China have shown increasing acceptance of green products. In the EU, 80% of respondents reported buying environmentally friendly products, and 77% indicated that they would be willing to pay more for such products if they were confident that they were truly environmentally friendly [5]. In China, survey evidence also shows that more than 70% of consumers are willing to pay higher prices for sustainable products [6]. This growing demand for green products is driving enterprises to integrate environmental sustainability into supply chain management.

Simultaneously, the rise of new retail models has brought both opportunities and challenges to green supply chain management [7,8]. By integrating online and offline channels through digital technologies, new retail can improve operational efficiency and strengthen information coordination across the supply chain [9]. However, this transition also involves considerable green cost pressures, including low-carbon technology investment, compliance costs, and infrastructure requirements for sustainable operations [10]. These challenges make it increasingly important for firms to balance economic performance and environmental responsibility in supply chain decisions.

In practice, firms facing green transition pressures usually respond along two particularly important dimensions. On the one hand, pricing decisions directly determine how consumer environmental awareness is translated into market demand and product competitiveness. On the other hand, carbon-related regulatory mechanisms directly affect firms' cost pressures and emission-reduction incentives across the supply chain [11–14]. Although other policy instruments such as subsidies, green credit, and technical standards are also relevant, pricing and carbon-related regulation are especially important because they simultaneously connect market response, firms' operational adjustment, and environmental governance. This practical background motivates our analysis of how pricing and emission-reduction decisions interact in green supply chains under different cooperation modes.

Against this backdrop, this paper investigates carbon reduction and pricing decisions in green supply chains under the joint influence of government carbon taxation and consumer environmental awareness. We address the following key questions: (1) How do governments, manufacturers, and retailers interact in such a system? (2) How does consumer environmental awareness influence firms' carbon reduction and pricing strategies? (3) How do different cooperation modes—non-cooperation, partial cooperation, and full cooperation—affect supply chain decision-making? (4) How should the government design an optimal carbon tax to balance environmental and economic goals? To this end, we develop a three-tier supply chain model involving a government, a manufacturer, and a retailer, and apply Stackelberg and Nash game frameworks to analyze strategic decisions under different cooperation structures. Numerical simulations are used to examine how varying levels of consumer environmental awareness affect carbon reduction efforts, pricing behavior, and corresponding government tax adjustments.

To achieve the above research objectives, we developed a systematic analytical framework integrating theoretical modeling and numerical analysis. First, we established a three-tier supply chain game-theoretic model involving a government, a manufacturer, and a retailer, employing Stackelberg and Nash game theories to examine four distinct cooperation scenarios. Second, we derived equilibrium solutions through backward induction methods, establishing mathematical relationships among carbon emission reduction levels, pricing strategies, and carbon tax policies. Finally, we designed numerical simulation experiments calibrated with industry data to examine nonlinear effects and validate theoretical predictions. The methodological innovation of this study lies in endogenizing government policy while incorporating alternative cooperation structures among supply

chain members, thereby providing a useful analytical framework for studying cooperation mechanisms in green supply chains.

The results indicate that increasing consumer environmental awareness motivates firms to strengthen emission-reduction efforts and may also affect the government's carbon tax decisions. Several nonlinear effects are identified. In particular, emission-reduction investment generally improves environmental performance in terms of emission intensity, but the extent of this improvement depends on market conditions. In markets with stronger environmental awareness, demand expansion associated with green preference may weaken the improvement in emission intensity. By contrast, in less environmentally sensitive markets, emission-reduction investment translates more directly into better environmental performance. These findings also highlight the role of cooperation mechanisms, particularly in shaping the alignment among pricing, abatement incentives, and overall supply chain performance.

The rest of this paper is organized as follows: Section 2 reviews the relevant literature and research progress on carbon reduction and pricing in green supply chains. Section 3 introduces the model structure and key parameter definitions. Section 4 presents the equilibrium analysis under different cooperation scenarios. Section 5 analyzes the effects of cooperation modes and consumer environmental awareness, and summarizes managerial and policy insights based on the theoretical and numerical results. Section 6 summarizes the key findings and offers directions for future research. Mathematical derivations and proofs are provided in Appendix A.

2. Literature Review

Against the backdrop of increasingly stringent carbon policies and growing demand for green consumption, research on green supply chain management has evolved to address more complex interactions among multiple stakeholders. This review focuses on two key streams directly relevant to our study: the impact of consumer environmental awareness on supply chain decisions, and carbon reduction and pricing strategies under policy interventions.

2.1. Impact of Consumer Environmental Awareness on Supply Chain Decisions

In recent years, with the increasing severity of environmental issues, the impact of consumer environmental awareness on GSCM has drawn growing academic attention. Studies have examined how green preferences influence firms' pricing, emission reduction, and channel strategies, thereby reshaping supply chain mechanisms. Ma et al. [15] analyzed pricing strategies for substitutable green products and argued that consumers' preference for eco-friendly products motivates firms to increase green investment, thereby affecting pricing. Liu and Ji [16] built a competitive supply chain model, revealing how consumer green preferences drive product selection and pricing policies. Liu et al. [17] found that stronger environmental awareness intensifies inter-firm competition and increases the pricing power of green products, though requiring higher emission reduction investment to meet demand. Wu and Yang [18] used a differential game model to explore the impact of low-carbon consumer preferences on dynamic optimization in supply chains, emphasizing the need for firms to adjust emission reduction strategies dynamically.

Numerous studies have also adopted game-theoretic perspectives to explore how consumer preferences interact with remanufacturing systems and carbon tax mechanisms. Zhang and Han [19] modeled a game between manufacturers and remanufacturers under carbon tax and product competition conditions, showing that heightened environmental awareness pushes manufacturers to lower new product prices and improve supply chain efficiency. Yang and You [20] found that rising environmental awareness helps expand

market share and fosters green innovation. Xu et al. [21], using the case of electric vehicles, showed that heightened environmental awareness affects market entry sequences and government subsidy design. Recent studies have further embedded consumer environmental awareness into more structured regulatory and supply-chain decision settings. Yang and Chen [22] examined retailer-driven carbon emission abatement under consumer environmental awareness and carbon tax, while Zhang and Qin [23] analyzed carbon reduction, pricing, and social welfare in a three-echelon supply chain under carbon tax policy and consumer environmental awareness.

Some scholars have extended the discussion to channel structure, green credit, and incentive mechanisms. Tao et al. [24] found that growing green awareness drives the evolution of product channels from single to hybrid forms, achieving balanced outcomes in multi-party games. Chen et al. [25] built an evolutionary game model integrating consumer recycling intentions and green finance tools to analyze the transformation path of the plastics supply chain under dual-carbon policies. Luo et al. [26], using the case of shore power, examined how environmental awareness affects policy selection and long-term sustainability goals. Lopes et al. [27] empirically tested the mediating effect of green attitudes on purchasing behavior, confirming that environmental cognition drives green marketing decisions. Recent empirical studies have provided further support for the consumer-driven demand mechanism in green markets. Nabi Khan et al. [28] showed that consumers' green perceptions and related behavioral factors significantly influence green purchase behavior within an extended theory of planned behavior framework. Cascavilla et al. [29] further provided experimental evidence that consumers show willingness to pay for sustainable products under appropriate market conditions. Sinh [30] examined the determinants of green consumption intention and behavior, while Hassan [31] showed that environmental concern, perceived usefulness, and green consumer knowledge can promote green consumer behavior. These studies provide recent empirical evidence that consumer-side green preferences can shape market demand.

At the same time, recent empirical studies suggest that the relationship between pro-environmental attitudes and actual green purchasing behavior is not always straightforward. Recio-Román et al. [32] found that favorable environmental attitudes do not necessarily translate into corresponding purchasing behavior, highlighting the existence of an attitude-behavior gap in green consumption. Therefore, while consumer environmental awareness is widely recognized as an important external driver of green supply chain transformation, its actual market effect should be interpreted with appropriate caution. In particular, consumer environmental awareness may affect market demand, willingness to pay, and firms' incentives for pricing and emission reduction only when such preferences are behaviorally effective. However, existing studies have largely examined government regulation, firms' decisions, and consumer green preference separately, and relatively limited attention has been paid to their joint effects within a unified analytical framework. In particular, less discussion has been devoted to how consumer environmental awareness may interact with endogenous carbon taxation and alternative cooperation structures in shaping pricing and emission-reduction outcomes. In this context, this paper develops a three-player game-theoretic framework involving a government, a manufacturer, and a retailer, while incorporating consumer environmental awareness as an exogenous market parameter, to further explore how these factors jointly affect supply chain performance.

2.2. Carbon Reduction and Pricing Decisions in Supply Chains

As sustainable development strategies deepen, carbon tax policies have gained increasing attention in supply chain management. Scholars have explored carbon emission costs, government regulations, and corporate emission reduction strategies. For example,

Hoehn et al. [33] examined how carbon emission regulations affect transport mode selection in supply chains. Benjaafar et al. [34] incorporated carbon footprints into supply chain operations and used optimization models to study decision adjustments for emission reductions. Carbon Trust [35] discussed the carbon emissions embedded in consumption, while Cachon [36] examined supply chain design under greenhouse gas emissions considerations.

Under carbon tax policies, supply chain pricing and emission reduction strategies have become central issues. Tian et al. [11] applied a multi-channel model to show that carbon tax levels directly affect firms' emission reduction incentives and pricing. Sundarakani et al. [12] emphasized that carbon prices impact both emission levels and profit margins. Xia et al. [37] investigated consumers' willingness to pay for green products from a consumer perspective in the context of green supply chain management. Gupta and Mishra [38] studied pricing and green quality decisions for substitutable green products in a two-stage green supply chain, highlighting the role of product substitutability in firms' strategic decisions. Zhang et al. [13] found that implementing carbon taxes and carbon trading alters production decisions, as rising costs are typically passed on to final product prices.

Although governments can encourage emission reductions via carbon taxes, excessively high tax rates may reduce sales and profits [11]. Research shows that moderate carbon tax levels can benefit supply chain performance. Governments should balance tax rates and subsidies to achieve optimal emission reduction goals. For instance, Ghosh and Shah [39] investigated pricing and emission decisions under cost-sharing contracts. Aslani and Heydari [40] explored the coordination of carbon taxes and pricing policies, concluding that a combination of taxes and subsidies can optimize supply chain performance. Zhang and Yu [41] proposed shared contracts to coordinate profit distribution and improve emission outcomes. In addition, some studies have explicitly modeled the interaction between government regulation and supply-chain decisions in multi-level game settings. Wang et al. [42] examined supply chain enterprise operations and government carbon tax decisions in a three-stage Stackelberg framework, while Chen et al. [43] analyzed a three-stage government–manufacturer–retailer game in the context of green product subsidies.

In summary, existing studies have provided important insights into carbon tax policies, firms' pricing decisions, emission-reduction strategies, consumer environmental awareness, and government regulation in green supply chains. Building upon this literature, this paper further examines how cooperation structures affect the interaction among carbon taxation, consumer environmental awareness, and firms' operational decisions. Although prior studies have analyzed these factors from different perspectives, most of them focus on a specific supply chain structure, policy setting, or cooperation arrangement. Relatively limited attention has been paid to incorporating carbon taxation, consumer environmental awareness, and alternative cooperation structures into a unified government–manufacturer–retailer framework. To address this gap, this paper develops a three-player game-theoretic model in which the government determines carbon tax policy, while the manufacturer and the retailer make pricing and emission-reduction decisions under four cooperation structures: non-cooperation, emission-reduction cooperation, pricing cooperation, and full cooperation. This setting enables us to examine not only the performance differences across cooperation modes, but also the mechanisms through which cooperation structures reshape carbon tax decisions, green investment incentives, market demand, and supply chain performance.

3. Problem Description

We consider a three-tier green supply chain consisting of a government (G), a manufacturer (M), and a retailer (R), under the dual influence of carbon taxation and consumer environmental awareness. This setting follows the multi-level Stackelberg-type modeling

logic commonly used in studies on environmental regulation and green supply chains, in which public regulation is determined first and firms subsequently adjust their pricing and emission-reduction decisions [23,42,43]. The government imposes a carbon tax on emissions from both the manufacturer and the retailer, thereby incentivizing low-carbon investment. The manufacturer determines the wholesale price ω and its carbon reduction level α_m , while the retailer sets the retail price p and chooses its own reduction effort α_r . The product is then sold to consumers.

The market demand Q depends linearly on the retail price and the total carbon reduction level, given by the function $Q = a + L(\alpha_m + \alpha_r) - \beta p$, where $L > 0$ reflects consumer environmental awareness and $\beta > 0$ denotes the price sensitivity. More specifically, in this paper, L is interpreted as behaviorally effective green preference, that is, environmental awareness that is sufficiently translated into actual purchasing tendencies and reflected in market demand, rather than merely stated pro-environmental attitudes [28,31,32]. This demand structure is consistent with previous studies [44,45]. To ensure economically meaningful equilibrium outcomes and the existence of interior solutions, we restrict the parameter space to $a - \beta p > 0$, $\beta k^2 > \frac{1}{2}$, and $L > \frac{2k\beta}{2\beta k^2 - 1}$. The condition $a - \beta p > 0$ guarantees positive market demand, while the latter two conditions help ensure the stability of the equilibrium solutions and avoid economically infeasible corner outcomes.

Consumer surplus (CS) is defined as the area under the inverse demand curve above the market price, computed as $CS = \frac{(a + L(\alpha_m + \alpha_r) - \beta p)^2}{2\beta}$, following Cohen et al. [46] and Peng et al. [47]. The social welfare function, used to represent government utility, includes the profits of supply chain members, consumer surplus, carbon tax revenue, and negative environmental externalities. It is defined as $\pi_G = \pi_m + \pi_r + CS + \theta(e_m + e_r) - (e_m + e_r)^2$, where θ is the unit carbon tax rate.

Carbon emissions are proportional to the market demand Q , with baseline emissions given by kQ . After investing in emission reductions, the effective emissions for the manufacturer and retailer are $e_m = kQ - \alpha_m$ and $e_r = kQ - \alpha_r$, respectively. Emission reduction costs are modeled as quadratic functions $\frac{1}{2}\alpha_m^2$ and $\frac{1}{2}\alpha_r^2$, reflecting diminishing marginal returns [48]. The interaction sequence in the supply chain is shown in Figure 1.

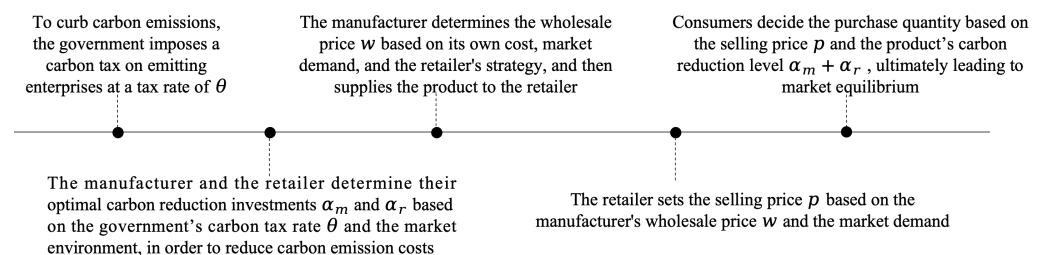


Figure 1. Sequence of events in the supply chain.

We examine four distinct cooperation modes: (1) non-cooperation (NC), where all parties make decisions independently; (2) emission reduction cooperation (CN), where the manufacturer and retailer jointly determine emission efforts; (3) pricing cooperation (NN), where retail prices are jointly set; and (4) full cooperation (OO), which is treated as a theoretical social-planner benchmark rather than a realistic commercial alliance. These four scenarios allow us to explore the interaction between policy, pricing, and environmental behavior in green supply chains. Model parameters are listed in Table 1.

Table 1. Notations used in this paper.

Notation	Definition
Model Parameters	
t	Unit production cost per product
a	Basic market demand within a certain range
L	Consumer environmental awareness level ($L > 0$)
β	Price sensitivity coefficient of market demand ($\beta > 0$)
k	Carbon emission coefficient per unit product
Decision Variables	
p	Retail price per unit product
ω	Wholesale price set by the manufacturer
θ	Carbon tax rate per unit emission
α_m	Carbon reduction level invested by the manufacturer
α_r	Carbon reduction level invested by the retailer
Performance Metrics	
Q	Market demand
e_m	Effective carbon emissions of the manufacturer
e_r	Effective carbon emissions of the retailer
e_{SC}	Total carbon emissions of the supply chain
EI_{SC}	Emission intensity of the supply chain
CS	Consumer surplus
π_r	Profit of the retailer
π_m	Profit of the manufacturer
π_G	Government (social) welfare
π_{SC}	Total profit of the supply chain system

4. Equilibrium Analysis

In this section, we construct and solve the equilibrium outcomes under four supply chain cooperation modes. Based on game theory, we analyze the optimal decision behaviors of the manufacturer and the retailer under different settings and examine how the government's carbon tax policy influences carbon reduction investments, pricing strategies, and social welfare. In addition, we compare the equilibrium outcomes across different cooperation modes to reveal the role and economic benefits of collaboration mechanisms in green supply chain management. We begin by constructing and analyzing three Stackelberg game models under the non-cooperative mode.

4.1. Equilibrium Analysis Under Non-Cooperation

In this subsection, we build game-theoretic models for three cooperation scenarios: non-cooperation (NC), carbon reduction cooperation (CN), and pricing cooperation (NN), and analyze their equilibrium solutions. Under the non-cooperative environment, the government, manufacturer, and retailer make decisions independently, each pursuing the maximization of their own profit, resulting in varying levels of market efficiency and social welfare. We construct and solve the corresponding game models sequentially.

4.1.1. Stackelberg Game Under Decentralized Decision-Making (NC Model)

In the NC model, the government, manufacturer, and retailer make independent decisions regarding both carbon reduction and pricing. Each supply chain member optimizes its own profit without any cooperative behavior. The overall decision process can be viewed as a multi-level game: the government acts as the leader and first sets the carbon tax rate θ to regulate corporate carbon emissions. The manufacturer, as the first follower, determines the wholesale price ω and carbon reduction investment α_m based on the tax rate. Then, the retailer, as the second follower, sets the retail price p and its own carbon

reduction investment α_r based on the manufacturer's decisions. This model can be divided into the carbon reduction stage and the pricing stage. The structure of the game is shown in Figure 2.

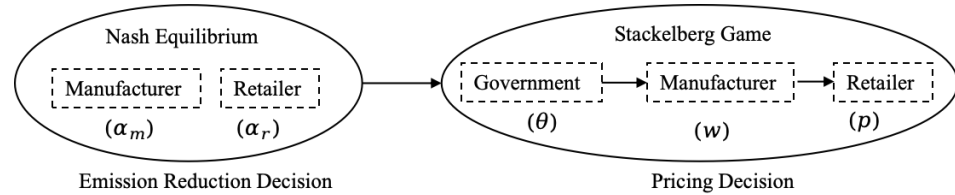


Figure 2. Game structure under the NC model.

Based on the above description, we begin with the pricing domain to analyze the decision-making process of supply chain members. The profit functions of the government, manufacturer, and retailer are given as follows:

$$\max_{\theta} \pi_G^{NC} = (p - t)[a + L(\alpha_m + \alpha_r) - \beta p] - \frac{1}{2}(\alpha_m^2 + \alpha_r^2) + \frac{(a + L(\alpha_m + \alpha_r) - \beta p)^2}{2\beta} - \frac{(e_m + e_r)^2}{2} \quad (1)$$

$$\text{s.t.} \begin{cases} \max_{\omega} \pi_M^{NC} = (\omega - t)[a + L(\alpha_m + \alpha_r) - \beta p] - \theta e_m - \frac{1}{2}\alpha_m^2 \\ \max_p \pi_R^{NC} = (p - \omega)[a + L(\alpha_m + \alpha_r) - \beta p] - \theta e_r - \frac{1}{2}\alpha_r^2 \end{cases} \quad (2)$$

Using backward induction, we solve this two-stage Stackelberg game to obtain the expressions for $\theta(\alpha_m, \alpha_r)$, $\omega(\alpha_m, \alpha_r)$, and $p(\alpha_m, \alpha_r)$. Substituting these into π_M^{NC} and π_R^{NC} , the manufacturer's and retailer's objective functions can be simplified as follows:

$$\begin{aligned} \max_{\alpha_m} \pi_M^{NC} = & \left[\frac{2(1 - 2\beta k^2)(a - \beta t)}{\beta(1 - 4\beta k^2)} + \frac{2[(1 - 2\beta k^2)L + 2\beta k](\alpha_m + \alpha_r)}{\beta(1 - 4\beta k^2)} \right] \\ & \cdot \left[\frac{(2\beta k^2 - 1)(a - \beta t)}{4\beta k^2 - 1} + \frac{(2\beta k^2 L - L - 2k\beta)(\alpha_m + \alpha_r)}{4\beta k^2 - 1} \right] \\ & + \frac{(4\beta k^2 - 3)(a - \beta t) + [(4\beta k^2 - 3)L - 8\beta k](\alpha_m + \alpha_r)}{2\beta k(1 - 4\beta k^2)} \cdot \alpha_m - \frac{1}{2}\alpha_m^2 \end{aligned} \quad (3)$$

$$\begin{aligned} \max_{\alpha_r} \pi_R^{NC} = & \left[\frac{(1 - 2\beta k^2)(a - \beta t)}{\beta(1 - 4\beta k^2)} + \frac{[(1 - 2\beta k^2)L + 2\beta k](\alpha_m + \alpha_r)}{\beta(1 - 4\beta k^2)} \right] \\ & \cdot \left[\frac{(2\beta k^2 - 1)(a - \beta t)}{4\beta k^2 - 1} + \frac{(2\beta k^2 L - L - 2k\beta)(\alpha_m + \alpha_r)}{4\beta k^2 - 1} \right] \\ & + \frac{(a - \beta t)(4\beta k^2 - 3) + [L(4\beta k^2 - 3) - 8\beta k](\alpha_m + \alpha_r)}{2\beta k(1 - 4\beta k^2)} \cdot \alpha_r - \frac{1}{2}\alpha_r^2 \end{aligned} \quad (4)$$

Theorem 1. In the NC model, the equilibrium strategies of the government, manufacturer, and retailer constitute a Stackelberg equilibrium. The closed-form solutions for the optimal carbon reduction levels, carbon tax rate, wholesale and retail prices, market demand, environmental performance, and profits are as follows:

- Optimal carbon reduction levels: $\alpha_m^{NC*} = f_m(a, t, \beta, k, L)$, $\alpha_r^{NC*} = f_r(a, t, \beta, k, L)$, where $f_m(\cdot)$ and $f_r(\cdot)$ are functions of market parameters and carbon reduction policies.
- Optimal carbon tax rate: $\theta^{NC*} = \frac{(a - \beta t)(4\beta k^2 - 3) + [L(4\beta k^2 - 3) - 8\beta k](\alpha_m^{NC*} + \alpha_r^{NC*})}{2\beta k(1 - 4\beta k^2)}$, capturing the relationship between government strategy and market equilibrium.
- Optimal pricing strategies:

$$\omega^{NC*} = \frac{a + L(\alpha_m^{NC*} + \alpha_r^{NC*}) + t\beta}{2\beta}$$

$$p^{NC*} = \frac{2k^2a + 2k(kL + 1)(\alpha_m^{NC*} + \alpha_r^{NC*}) + (2\beta k^2 - 1)t}{4\beta k^2 - 1}$$

- *Market demand:*

$$Q^{NC*} = \frac{(2\beta k^2 - 1)(a - \beta t) + (2\beta k^2 L - L - 2k\beta)(\alpha_m^{NC*} + \alpha_r^{NC*})}{4\beta k^2 - 1}$$

- *Environmental performance:*

$$e_{SC}^{NC*} = e(a, t, \beta, k, L, \alpha_m^{NC*}, \alpha_r^{NC*}), \quad EI_{SC}^{NC*} = \frac{e_{SC}^{NC*}}{Q^{NC*}}$$

- *Profits: π_m^{NC*} , π_r^{NC*} , and π_G^{NC*} .*

Proof. The explicit expressions are provided in Appendix A. $\square$

The results show that in the non-cooperative model, the carbon reduction investments of the manufacturer and retailer depend on market demand, consumer environmental awareness, and the government's carbon tax policy. The tax rate directly affects carbon emissions, pricing, and demand, and ultimately the profit of supply chain members.

Proposition 1. In the NC model, define emission intensity as $EI_{SC}^{NC*} = \frac{e_{SC}^{NC*}}{Q^{NC*}}$. Let $\alpha = \alpha_m^{NC*} + \alpha_r^{NC*}$. When $a - \beta t > 0$ and $\frac{1}{2} < \beta k^2 < \frac{3}{4}$, the emission intensity EI_{SC}^{NC*} decreases with the increase in the emission-reduction efforts α .

Proof. Please refer to Appendix A. $\square$

This result indicates that emission-reduction investment improves environmental performance in terms of emission intensity. In particular, as the total emission-reduction effort increases, the environmental burden per unit of demand declines. However, the extent of this improvement still depends on market conditions. In markets with strong environmental awareness, demand expansion induced by green preference may weaken the improvement in emission intensity. By contrast, in markets with weaker environmental consciousness, emission-reduction investment translates more directly into better environmental performance. These findings suggest that the effectiveness of green investment is closely related to the level of consumer environmental awareness, and that carbon policies should be designed in a way that balances technological progress with market expansion.

Proposition 2. In the NC model, when $\frac{1}{2} < \beta k^2 < \frac{3}{4}$, the optimal carbon tax rate θ^{NC*} , wholesale price ω^{NC*} , and retail price p^{NC*} all increase with the rise in emission-reduction efforts $\alpha_m^{NC*} + \alpha_r^{NC*}$. In addition, market demand Q^{NC*} increases with the rise in emission-reduction efforts when $L > \frac{2\beta k}{2\beta k^2 - 1}$.

Proof. Please refer to Appendix A. $\square$

This result reflects the joint influence of green investment, market response, and policy adjustment under relatively strong consumer environmental awareness. In environmentally conscious markets, consumers are more willing to purchase greener products. As manufacturers and retailers increase their emission-reduction efforts, product value is enhanced, which contributes to higher prices and stronger market demand. At the same time, the model implies a higher carbon tax level, indicating that policy intervention may strengthen along with the progress of green transition. Therefore, emission-reduction investment

affects not only firms' pricing and demand outcomes, but also the policy environment in which the supply chain operates.

4.1.2. Stackelberg Game with Manufacturer–Retailer Cooperation in Carbon Reduction (CN Model)

In the CN model, the manufacturer and retailer collaborate on carbon reduction decisions, jointly determining the optimal level of emission reductions to improve the environmental performance of the supply chain. However, regarding pricing decisions, the manufacturer and retailer still act independently, each maximizing its own profit. This partial cooperation pattern is common in real-world supply chains, especially when both entities belong to the same group (e.g., Nike), where manufacturing and retail operations are integrated under a unified system, facilitating internal cooperation on carbon reduction. The pricing process in the CN model follows that of the NC model and is therefore omitted here. The focus is on how emission reduction cooperation affects supply chain equilibrium. Figure 3 illustrates the sequence of decisions and game structure in the CN model.

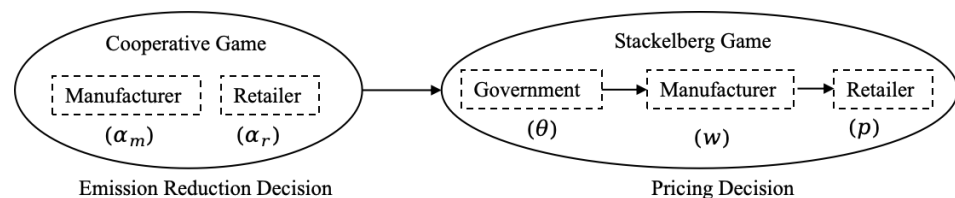


Figure 3. Game structure under the CN model.

In the CN model, the manufacturer and retailer jointly maximize their combined profit by optimizing carbon reduction strategies:

$$\max_{\alpha_m, \alpha_r} \pi_{M+R}^{CN} = \pi_M^{CN} + \pi_R^{CN} \quad (5)$$

The combined profit is expressed as:

$$\pi_{M+R}^{CN} = (p - t - 2\theta k)[a + L(\alpha_m + \alpha_r) - \beta p] + \theta(\alpha_m + \alpha_r) - \frac{1}{2}(\alpha_m^2 + \alpha_r^2) \quad (6)$$

Substituting the demand function and Stackelberg equilibrium conditions, the joint profit can be rewritten as:

$$\begin{aligned} \pi_{M+R}^{CN} = & \left[\frac{3(a - \beta t)(1 - 2\beta k^2)}{\beta(1 - 4\beta k^2)} - \frac{3(2\beta k^2 L - L - 2\beta k)(\alpha_m + \alpha_r)}{\beta(1 - 4\beta k^2)} \right] \\ & \times \left[\frac{(1 - 2\beta k^2)(a - \beta t)}{1 - 4\beta k^2} + \frac{(2\beta k^2 L - L - 2\beta k)(\alpha_m + \alpha_r)}{4\beta k^2 - 1} \right] \\ & + \frac{(a - \beta t)(4\beta k^2 - 3)(\alpha_m + \alpha_r) + [L(4\beta k^2 - 3) - 8\beta k](\alpha_m + \alpha_r)^2}{2\beta k(1 - 4\beta k^2)} \\ & - \frac{1}{2}(\alpha_m^2 + \alpha_r^2) \end{aligned} \quad (7)$$

Theorem 2. In the CN model, the equilibrium solutions are as follows:

- Optimal carbon reduction levels:

$$\alpha_m^{CN*} = \alpha_r^{CN*} = \frac{(\beta t - a)[12kL(2\beta k^2 - 1)^2 - 64\beta^2 k^4 + 40\beta k^2 - 3]}{24k(2\beta k^2 L - L - 2\beta k)^2 + (1 - 4\beta k^2)[4L(4\beta k^2 - 3) - 2\beta k(17 - 4\beta k^2)]}$$

- *Environmental performance:*

$$e_{SC}^{CN*} = e(a, t, \beta, k, L, \alpha_m^{CN*}, \alpha_r^{CN*}), \quad EI_{SC}^{CN*} = \frac{e_{SC}^{CN*}}{Q^{CN*}}$$

- *Optimal carbon tax rate:* $\theta^{CN*} = \frac{(a-\beta t)(4\beta k^2-3)+[L(4\beta k^2-3)-8\beta k](\alpha_m^{CN*}+\alpha_r^{CN*})}{2\beta k(1-4\beta k^2)}$

- *Optimal pricing:*

$$\omega^{CN*} = \frac{a + L(\alpha_m^{CN*} + \alpha_r^{CN*}) + \beta t}{2\beta}$$

$$p^{CN*} = \frac{2k^2a + 2k(kL + 1)(\alpha_m^{CN*} + \alpha_r^{CN*}) + (2\beta k^2 - 1)t}{4\beta k^2 - 1}$$

- *Market demand:*

$$Q^{CN*} = \frac{(2\beta k^2 - 1)(a - \beta t) + (2\beta k^2 L - L - 2k\beta)(\alpha_m^{CN*} + \alpha_r^{CN*})}{4\beta k^2 - 1}$$

- *Total profit of manufacturer and retailer:* $\pi_{M+R}^{CN*} = f_{m+r}(a, t, \beta, k, L, \alpha_m^{CN*}, \alpha_r^{CN*})$
- *Government profit:* $\pi_G^{CN*} = f_g(p, Q, t, \beta, k, \alpha_m^{CN*}, \alpha_r^{CN*})$

Proof. The explicit expressions are provided in Appendix A. $\square$

Building on the above equilibrium results, we further analyze the nonlinear impacts of emission reduction efforts under different levels of environmental awareness, as shown in the following proposition.

Proposition 3. In the CN model, define emission intensity as $EI_{SC}^{CN*} = \frac{e_{SC}^{CN*}}{Q^{CN*}}$. Let $\alpha = \alpha_m^{CN*} + \alpha_r^{CN*}$. When $a - \beta t > 0$ and $\frac{1}{2} < \beta k^2 < \frac{3}{4}$, the emission intensity EI_{SC}^{CN*} decreases with the increase in the emission-reduction efforts α .

Proof. Please refer to Appendix A. $\square$

Compared with Proposition 1, the CN model shows a similar tendency in environmental performance when measured by emission intensity, but cooperation in emission reduction helps improve the overall environmental outcome. In particular, under the CN model, joint emission-reduction decisions between the manufacturer and the retailer can strengthen the effectiveness of low-carbon investment.

At the same time, the extent of improvement in emission intensity still depends on market conditions. In markets with strong consumer environmental awareness, demand expansion associated with greener products may weaken the improvement in emission intensity. By contrast, in markets with weaker environmental consciousness, emission-reduction investment translates more directly into better environmental performance. These results suggest that carbon taxation and emission-reduction cooperation jointly contribute to improving the environmental performance of the supply chain.

Proposition 4. In the CN model, when $\frac{1}{2} < \beta k^2 < \frac{3}{4}$, the optimal carbon tax rate θ^{CN*} , wholesale price ω^{CN*} , and retail price p^{CN*} all increase with the rise in emission-reduction efforts $\alpha_m^{CN*} + \alpha_r^{CN*}$. Compared with the NC model, emission-reduction cooperation in the CN model helps partially alleviate the cost burden, although the upward trend in prices remains.

Proof. Please refer to Appendix A. $\square$

This result suggests that emission-reduction cooperation between the manufacturer and the retailer can partially share the cost of green investment, but it does not fundamentally change the cost pass-through mechanism in the supply chain. As carbon taxes rise with stronger emission-reduction efforts, firms still face upward pressure on pricing. Since the CN model coordinates emission reduction but not pricing decisions, the benefits of cost sharing cannot be fully transmitted to the market. As a result, product prices continue to increase, which indicates the importance of further coordination in pricing decisions.

4.1.3. Stackelberg Game with Joint Pricing Under Decentralized Emission Decisions (NN Model)

In the NN model, supply chain members independently decide their carbon reduction levels while forming a joint alliance in pricing decisions, where the final retail price is determined collaboratively. This model reflects real-world practices, such as Walmart's private label pricing, which is often determined through internal negotiations within its supply chain.

The Stackelberg game structure remains: the government, as the leader, sets the carbon tax rate θ , followed by the manufacturer–retailer alliance as the follower, which sets the product price p . Figure 4 illustrates the decision sequence and game structure in the NN model.

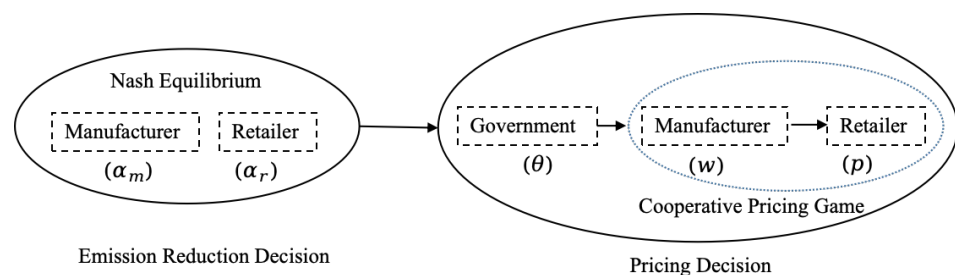


Figure 4. Game structure under the NN model.

Profit maximization functions under pricing decisions:

$$\max_{\theta} \pi_G^{NN} = (p - t)(a + L(\alpha_m + \alpha_r) - \beta p) - \frac{1}{2}(\alpha_m^2 + \alpha_r^2) + \frac{(a + L(\alpha_m + \alpha_r) - \beta p)^2}{2\beta} - \frac{(e_m + e_r)^2}{2} \quad (8)$$

$$\max_p \pi_{M+R}^{NN} = \pi_M^{NN} + \pi_R^{NN} = (p - t - 2\theta k)(a + L(\alpha_m + \alpha_r) - \beta p) + \theta(\alpha_m + \alpha_r) - \frac{1}{2}(\alpha_m^2 + \alpha_r^2) \quad (9)$$

Using backward induction, we derive the best responses $\theta(\alpha_m, \alpha_r)$ and $p(\alpha_m, \alpha_r)$. Substituting these into π_M^{NN} and π_R^{NN} yields their respective objective functions (see Appendix A for derivations).

Theorem 3. In the NN model, the equilibrium results are as follows:

- Optimal carbon reduction levels:

$$\alpha_m^{NN*} = \alpha_r^{NN*} = \frac{2\beta k(\omega - t)(1 + 4\beta k^2)(L + 2\beta k) + 2k(a - \beta t)[2\beta k - (4\beta k^2 - 1)(L + \beta k)]}{4k(L + 2\beta k)[(4\beta k^2 - 1)L - 4\beta k] + (1 + 4\beta k^2)[2\beta k(7 + 4\beta k^2) - 3(4\beta k^2 - 1)(a - \beta t + L)]}$$

- Environmental performance:

$$e_{SC}^{NN*} = \frac{2k(a - \beta t) + (2kL - 1)(\alpha_m^{NN*} + \alpha_r^{NN*})}{1 + 4\beta k^2} - (\alpha_m^{NN*} + \alpha_r^{NN*}), EI_{SC}^{NN*} = \frac{e_{SC}^{NN*}}{Q^{NN*}}$$

- Optimal carbon tax:

$$\theta^{NN*} = \frac{(4\beta k^2 - 1)[a + L(\alpha_m^{NN*} + \alpha_r^{NN*}) - \beta t] - 4\beta k(\alpha_m^{NN*} + \alpha_r^{NN*})}{2\beta k(1 + 4\beta k^2)}$$

- Optimal retail price:

$$p^{NN*} = \frac{4k^2[a + L(\alpha_m^{NN*} + \alpha_r^{NN*})] + t - 2k(\alpha_m^{NN*} + \alpha_r^{NN*})}{1 + 4\beta k^2}$$

- Market demand:

$$Q^{NN*} = \frac{a + (L + 2\beta k)(\alpha_m^{NN*} + \alpha_r^{NN*}) - \beta t}{1 + 4\beta k^2}$$

- Manufacturer and retailer joint profit: π_{M+R}^{NN*}
- Government profit: π_G^{NN*}

Proof. The explicit expressions are provided in Appendix A. $\square$

Building on the equilibrium outcomes under the NN model, we further explore the environmental performance and nonlinear effects arising from pricing cooperation.

Proposition 5. In the NN model, define emission intensity as $EI_{SC}^{NN*} = \frac{e_{SC}^{NN*}}{Q^{NN*}}$. Let $\alpha = \alpha_m^{NN*} + \alpha_r^{NN*}$. When $a - \beta t > 0$, the emission intensity EI_{SC}^{NN*} decreases with the increase in the emission-reduction efforts α .

Proof. Please refer to Appendix A. $\square$

This result indicates that emission-reduction investment improves environmental performance in the NN model when measured by emission intensity. As the total emission-reduction effort increases, the environmental burden per unit of demand declines. However, the extent of this improvement still depends on market conditions. In markets with strong environmental awareness, demand expansion induced by green preference may weaken the improvement in emission intensity. By contrast, in markets with weaker environmental consciousness, emission-reduction investment translates more directly into better environmental performance. These findings suggest that pricing cooperation alone can improve environmental performance, but its effectiveness still depends on market demand conditions.

Proposition 6. In the NN model, market demand Q^{NN*} increases with the rise in emission-reduction efforts $\alpha_m^{NN*} + \alpha_r^{NN*}$. Moreover, when $L > \frac{4\beta k}{4\beta k^2 - 1}$ and $\frac{1}{2} < \beta k^2 < \frac{3}{4}$, the optimal carbon tax rate θ^{NN*} and retail price p^{NN*} also increase with the rise in emission-reduction efforts.

Proof. Please refer to Appendix A. $\square$

This result reflects a possible green-growth pattern induced by emission-reduction investment in the NN model. In markets with strong environmental awareness, stronger emission-reduction efforts may lead to higher carbon tax rates, higher product prices, and stronger market demand at the same time. This suggests that green transition can coexist with market expansion under pricing cooperation. However, since the environmental performance of the supply chain should be evaluated more appropriately in terms of emission intensity, market-driven demand growth alone may not be sufficient to guarantee

stronger overall environmental gains. This highlights the importance of combining pricing cooperation with appropriate policy support.

4.2. Equilibrium Analysis Under Full Cooperation (OO Model)

The OO model is used as a benchmark case for a fully coordinated decision environment oriented toward total social welfare maximization. In this setting, the government acts as a regulator representing social welfare rather than a supply chain participant. The manufacturer and the retailer coordinate pricing and emission-reduction decisions under this welfare-oriented benchmark. Figure 5 presents the decision sequence and game structure under the OO model.

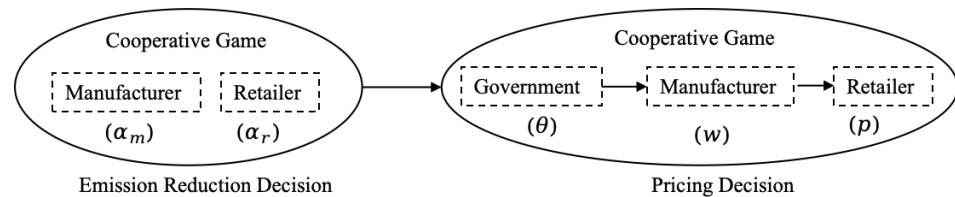


Figure 5. Decision sequence and game structure under the OO model.

Profit function for the supply chain system (pricing decision):

$$\begin{aligned} \max_p \pi_{SC}^{OO} &= \pi_G^{OO} + \pi_M^{OO} + \pi_R^{OO} \\ &= 2[p - t - k\theta + k(\alpha_m + \alpha_r)][a + L(\alpha_m + \alpha_r) - \beta p] \\ &\quad + \frac{1 - 4\beta k^2}{2\beta} [a + L(\alpha_m + \alpha_r) - \beta p]^2 \\ &\quad + \theta(\alpha_m + \alpha_r) - \left(\frac{3}{2}\alpha_m^2 + \frac{3}{2}\alpha_r^2 + \alpha_m\alpha_r \right) \end{aligned} \quad (10)$$

By calculating the second-order derivative of π_{SC}^{OO} with respect to p , we obtain $p(\alpha_m, \alpha_r)$. Substituting this into the overall profit function yields:

$$\begin{aligned} \max_{\alpha_m, \alpha_r} \pi_{SC}^{OO} &= \frac{3 + 4\beta k^2}{2\beta(1 + 4\beta k^2)^2} [a + (L + 2\beta k)(\alpha_m + \alpha_r) - \beta t]^2 \\ &\quad + \frac{(\beta t - a)(1 - 4\beta k^2)(\alpha_m + \alpha_r) - (L + 4\beta k - 4\beta k^2 L)(\alpha_m + \alpha_r)^2}{2k\beta(1 + 4\beta k^2)} \\ &\quad - \left(\frac{3}{2}\alpha_m^2 + \frac{3}{2}\alpha_r^2 + \alpha_m\alpha_r \right) \end{aligned} \quad (11)$$

Based on this cooperative game framework, we derive the optimal carbon reduction levels, retail price, market demand, supply chain profits, and social welfare (see Appendix A for explicit expressions).

Proposition 7. In the OO model, define emission intensity as $EI_{SC}^{OO*} = \frac{e_{SC}^{OO*}}{Q^{OO*}}$. Let $\alpha = \alpha_m^{OO*} + \alpha_r^{OO*}$. When $a - \beta t > 0$, the emission intensity EI_{SC}^{OO*} decreases with the increase in the emission-reduction efforts α .

Proof. Please refer to Appendix A. $\square$

Proposition 8. In the OO model, market demand Q^{OO*} increases with the rise in emission-reduction efforts $\alpha_m^{OO*} + \alpha_r^{OO*}$. Moreover, when $L > \frac{4\beta k}{4\beta k^2 - 1}$ and $\frac{1}{2} < \beta k^2 < \frac{3}{4}$, the optimal carbon tax rate θ^{OO*} also increases with the rise in emission-reduction efforts. In addition, when $L > \frac{1}{2k}$, the optimal retail price p^{OO*} increases with the rise in emission-reduction efforts.

Proof. Please refer to Appendix A. $\square$

Compared with the other three models (NC, CN, and NN), the OO model is characterized by a more comprehensive cooperation structure. Under full cooperation, manufacturers and retailers coordinate both emission-reduction and pricing decisions, which helps strengthen the overall effectiveness of green investment and policy implementation. By contrast, the NC, CN, and NN models each coordinate only part of the decision process, so their environmental and market effects are relatively less integrated.

From Propositions 1, 3, 5 and 7, it can be seen that stronger consumer environmental awareness encourages firms to invest more in emission reduction and generally improves environmental performance in terms of emission intensity. At the same time, stronger green preference may stimulate market demand, which can weaken the extent of improvement in environmental performance. This suggests that the effectiveness of green investment depends not only on technological progress, but also on market demand conditions.

From Propositions 2, 4, 6 and 8, when consumers are willing to pay a green premium, stronger emission-reduction efforts are associated with higher carbon tax levels and higher product prices. This indicates that green transition may proceed together with market expansion and policy adjustment. In the long run, such interactions can strengthen the coordination between market mechanisms and environmental regulation, guiding firms to balance profitability and sustainability.

5. Model Analysis and Managerial Insights

To better examine how cooperation modes and consumer environmental awareness jointly affect decision-making and performance in the green supply chain, this section presents a comparative and sensitivity analysis of key variables under different models.

5.1. Comparative and Sensitivity Analysis

This section compares the equilibrium outcomes across the four cooperation structures and then examines how consumer environmental awareness affects the main equilibrium outcomes through sensitivity analysis.

We begin with a benchmark comparison under the baseline parameter setting. The results show that different cooperation structures lead to distinct economic and operational outcomes. Partial cooperation (CN and NN) strengthens abatement incentives to different degrees, while the OO model exhibits a relatively lower total abatement level but generates the highest market demand and supply chain profit. This is because CN and NN remain largely profit-oriented and use abatement to enhance market competitiveness or alleviate regulatory pressure, whereas the OO model balances the marginal benefits and costs of abatement under a welfare-oriented benchmark. These patterns suggest that cooperation may improve efficiency, but its effects on abatement incentives, market response, and profitability are not necessarily aligned. Figure 6 illustrates the benchmark comparison of total carbon reduction levels across models.

To investigate the effect of consumer environmental awareness on decision-making, we vary the green preference parameter L within the range $[3.1, 3.9]$ and perform sensitivity analyses on the key equilibrium outcomes. We consider two levels of total carbon reduction capability, $\alpha_m + \alpha_r = 1$ and $\alpha_m + \alpha_r = 4$. The other parameter values are fixed at $a = 45$, $\beta = 0.9$, $t = 10$, $k = 0.833$, and $w = 20$.

As shown in Figure 7, the optimal carbon tax rate generally increases with L across models. This occurs because stronger consumer environmental awareness raises the market value of green products and encourages firms to expand green investment and production. As the demand-expansion effect of green products becomes stronger, the government has greater incentives to adjust the carbon tax rate to balance market growth and environmental

protection. The effect is more pronounced when higher abatement capability makes policy intervention more consequential.

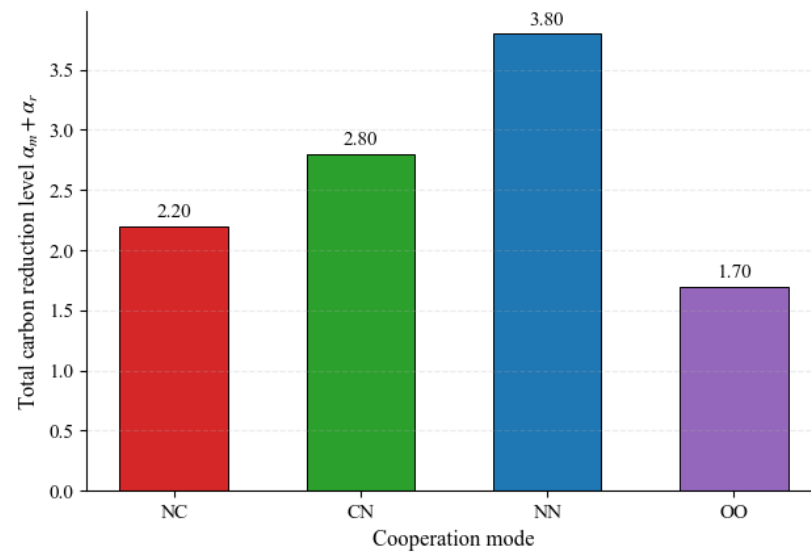


Figure 6. Benchmark comparison of total carbon reduction levels across cooperation modes.

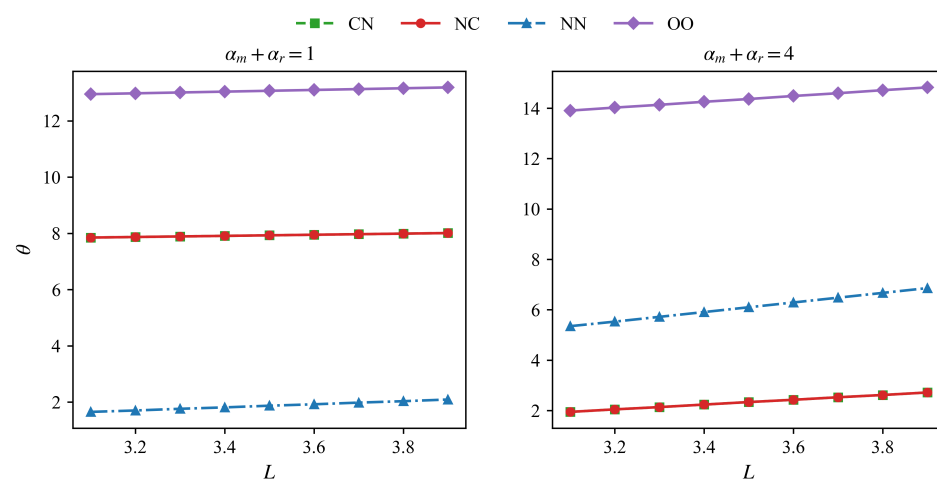


Figure 7. Effect of consumer environmental awareness L on the carbon tax rate θ under two total abatement scenarios.

Figure 8 shows that retail prices increase with L in all models. However, the OO model exhibits relatively lower price growth, suggesting that fuller coordination helps mitigate cost pass-through to consumers. This is because the OO model coordinates pricing and emission-reduction decisions under a welfare-oriented benchmark, allowing part of the green investment cost to be internalized at the system level. By contrast, in the CN and NC models, pricing decisions remain insufficiently coordinated, so a larger share of abatement-related costs is reflected in higher retail prices.

Figure 9 shows that market demand increases with L , with the strongest response observed under the OO model. This is because stronger consumer environmental awareness raises consumers' preference for low-carbon products, and the OO model coordinates pricing and emission-reduction decisions under a welfare-oriented benchmark, enabling green preference to be more effectively converted into market demand. By contrast, demand changes more modestly under less coordinated structures, suggesting that cooperation can strengthen the transmission of green preference into actual consumption.

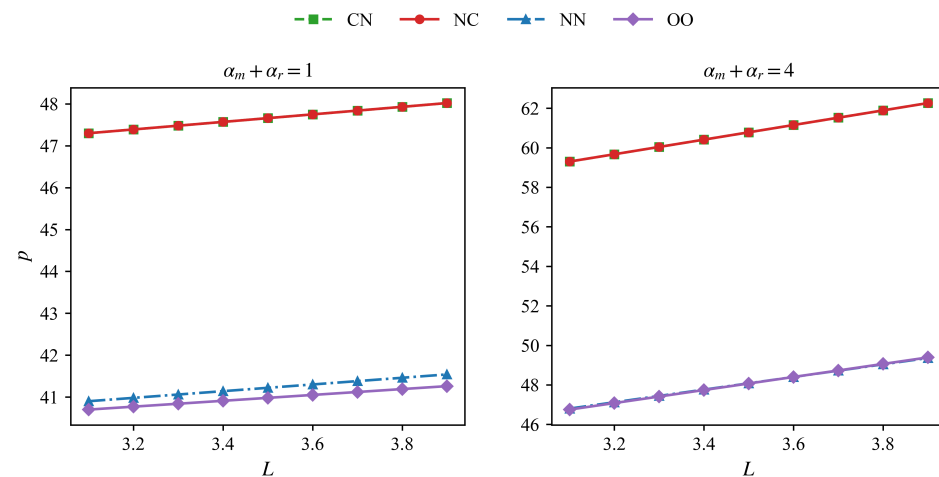


Figure 8. Effect of consumer environmental awareness L on retail price p under two total abatement scenarios.

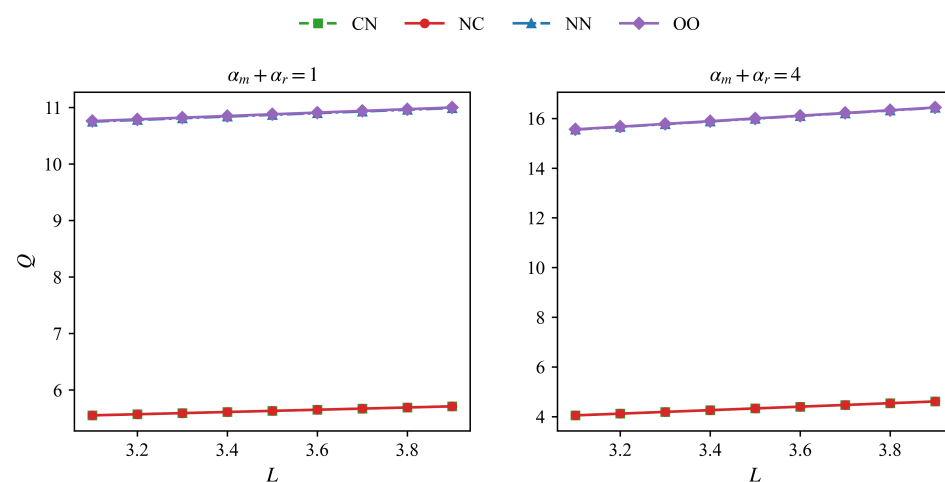


Figure 9. Effect of consumer environmental awareness L on market demand Q under two total abatement scenarios.

In terms of supply chain profitability, Figure 10 shows that supply chain profit is highest in the OO model across all values of L . This is because the OO model jointly optimizes pricing and emission-reduction decisions from a system-wide perspective, thereby improving overall resource allocation efficiency. The NN model also performs well, as pricing cooperation helps mitigate double marginalization and enables firms to better capture the demand-expansion effect generated by green investment, whereas the CN model may underperform the NC model despite stronger abatement incentives. This suggests that emission-reduction cooperation alone does not necessarily improve economic performance when the pricing side remains insufficiently coordinated. In this case, additional abatement costs may not be fully converted into market gains, leading to weaker profit performance.

To further examine the robustness of the numerical findings, we further investigate the effects of the emission coefficient k and the price sensitivity coefficient β on the optimal carbon tax rate. Figure 11 shows that although changes in k and β affect the absolute level of the optimal carbon tax rate, the relative comparison across different cooperation modes remains broadly unchanged. Specifically, the NC and CN models are more sensitive to parameter variations, whereas the NN and OO models generate relatively stable carbon tax outcomes. This indicates that pricing coordination and system-level coordination can partially buffer the influence of market and environmental changes on policy design.

Therefore, the main conclusions regarding the relationship between cooperation structures and carbon tax design remain robust under alternative parameter settings.

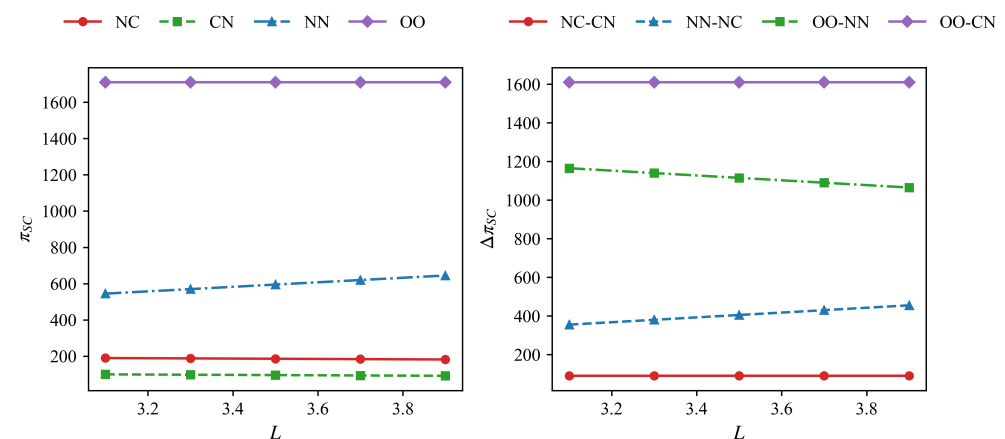


Figure 10. Effect of consumer environmental awareness L on supply chain profit π_{SC} and pairwise profit differences.

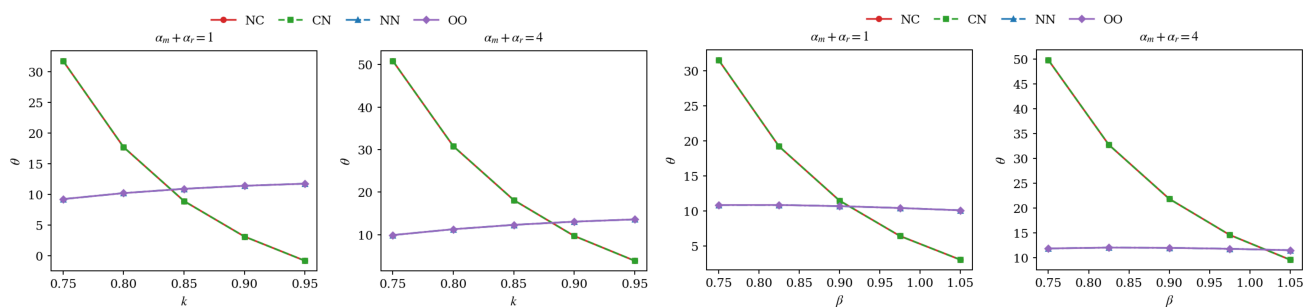


Figure 11. Robustness analysis: effects of the emission coefficient k and price sensitivity coefficient β on the optimal carbon tax rate θ .

Overall, these results show that cooperation structure, cost-sharing arrangements, consumer environmental awareness, price sensitivity, and emission intensity interact in complex ways in shaping taxation, pricing, demand, and profitability. They also suggest that stronger coordination does not uniformly improve all outcomes, but rather changes the balance among abatement incentives, market expansion, and economic performance.

5.2. Managerial and Policy Implications

Based on the theoretical and numerical results, the following implications can be drawn.

(1) Different cooperation structures lead to different economic and environmental outcomes. Coordination mechanisms are generally expected to improve supply chain performance under environmental regulation, while our analysis further shows that their effects differ across cooperation structures. In particular, by comparing the NC, CN, NN, and OO models within a unified framework, this study shows that pricing cooperation provides relatively strong incentives for emission reduction, whereas full cooperation achieves a better balance between environmental and economic performance. This suggests that managers should not only pursue cooperation in general, but also pay attention to the specific form of cooperation adopted in practice.

(2) The effectiveness of carbon taxation depends on the underlying cooperation structure. Our results indicate that the effect of carbon taxation is closely related to the coordination structure within the supply chain. By explicitly modeling the government as an endogenous decision-maker, we find that the same carbon policy may lead to different

pricing, demand, and performance outcomes under alternative cooperation modes. Therefore, policymakers should consider not only the level of carbon taxation itself, but also the coordination pattern within the supply chain when designing regulatory instruments.

(3) The environmental benefits of green investment may be influenced by market expansion. Our results show that emission-reduction investment generally improves environmental performance, but the extent of this improvement depends not only on technological effort itself, but also on changes in market demand. In particular, in markets with stronger consumer environmental awareness, demand expansion associated with green preference may weaken the environmental gains from emission-reduction investment. This implies that firms should pay attention not only to green investment itself, but also to how market expansion may affect the actual environmental benefits of such investment.

(4) Consumer environmental awareness reshapes both market response and policy transmission. Prior studies have emphasized that green consumer preference affects firms' pricing and green investment decisions. Building on this view, our analysis further indicates that consumer environmental awareness also influences how cooperation structures and carbon taxation interact. In markets with stronger environmental awareness, firms may obtain greater pricing power and stronger demand responses, while policy intervention may also become more pronounced. Therefore, managers should incorporate demand-side green preference into strategic planning, and policymakers should recognize that the effectiveness of environmental regulation may vary with the environmental maturity of the consumer market.

Overall, the value of this study lies not in proposing entirely different policy conclusions, but in providing a unified comparative framework for analyzing the joint effects of government carbon taxation, cooperation structures, and consumer environmental awareness.

6. Conclusions

This paper develops a three-tier game-theoretic model to analyze a green supply chain composed of a government, a manufacturer, and a retailer under the dual influence of carbon taxation and consumer environmental awareness. By constructing a unified analytical framework, we systematically compare four cooperation modes—non-cooperative, emission reduction cooperation, pricing cooperation, and full cooperation—and investigate their impacts on carbon reduction, pricing, carbon tax design, demand response, and profit distribution. The model incorporates consumer environmental awareness into the demand function and endogenizes the government's carbon tax response, offering a structured approach to analyze the strategic interactions among the government, manufacturer, and retailer in green supply chains.

This study makes several contributions. First, it develops a unified three-player game-theoretic framework to examine the interactions among the government, manufacturer, and retailer in green supply chains. By comparing four distinct cooperation structures and endogenizing the government's carbon tax policy, it extends the analytical framework for joint pricing and emission-reduction decisions. Second, it incorporates a flexible demand function that captures consumer environmental awareness, enabling a richer characterization of green consumption behavior. Third, it identifies several nonlinear and policy-sensitive response mechanisms, including the role of emission intensity as an environmental performance indicator and the way demand expansion may weaken the environmental gains from emission-reduction investment under strong consumer environmental awareness. These findings are derived through theoretical analysis and simulation, providing both theoretical enrichment and practical insights for policy design and enterprise collaboration.

This study has certain limitations. In particular, the model assumes a relatively strong and consistent translation from consumer environmental awareness into actual purchasing behavior. However, in real markets, pro-environmental attitudes and stated willingness to pay do not always translate fully into corresponding purchasing decisions. Therefore, the effect of consumer environmental awareness in this paper should be understood under the condition that such preferences are behaviorally effective. Future research could extend this work in several directions. First, more realistic consumer behavior, such as the attitude–behavior gap, bounded rationality, and preference heterogeneity, could be incorporated into the model. Second, a dynamic framework could be developed to examine long-term strategic interactions and the evolution of carbon policies. Third, future studies may further explore the joint effects of multiple regulatory instruments, such as carbon taxes, emissions trading schemes, and green subsidies, to provide more comprehensive insights for sustainable supply chain governance.

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Appendix A. Proof of Theorem and Proposition

Appendix A.1. Proof of the NC Model

The following expressions represent the optimal decisions and profit outcomes derived in Theorem 1 under the NC model:

$$\begin{aligned}
 e_{SC}^{NC*} &= \frac{2k(2\beta k^2 - 1)a - 2k(2\beta k^2 - 1)\beta t + 2k(2\beta k^2 L - L - 2k\beta)(\alpha_m^{NC*} + \alpha_r^{NC*})}{4\beta k^2 - 1} - (\alpha_m^{NC*} + \alpha_r^{NC*}) \\
 \theta^{NC*} &= \frac{(a - \beta t)(4\beta k^2 - 3) + [L(4\beta k^2 - 3) - 8\beta k](\alpha_m^{NC*} + \alpha_r^{NC*})}{2\beta k(1 - 4\beta k^2)} \\
 \omega^{NC*} &= \frac{a + L(\alpha_m^{NC*} + \alpha_r^{NC*}) + t\beta}{2\beta} \\
 p^{NC*} &= \frac{2k^2 a + 2k(kL + 1)(\alpha_m^{NC*} + \alpha_r^{NC*}) + (2\beta k^2 - 1)t}{4\beta k^2 - 1} \\
 Q^{NC*} &= \frac{(2\beta k^2 - 1)(a - \beta t) + (2\beta k^2 L - L - 2k\beta)(\alpha_m^{NC*} + \alpha_r^{NC*})}{4\beta k^2 - 1}
 \end{aligned}$$

$$\begin{aligned}
\pi_G^{NC*} &= (p^{NC*} - t - 2k^2 Q^{NC*}) Q^{NC*} + \frac{(Q^{NC*})^2}{2\beta} \\
&\quad + \left[2k Q^{NC*} - (\alpha_m^{NC*} + \alpha_r^{NC*}) \right] (\alpha_m^{NC*} + \alpha_r^{NC*}) + \alpha_m^{NC*} \alpha_r^{NC*} \\
\pi_r^{NC*} &= \left[\frac{(a - t\beta)(1 - 2\beta k^2)}{\beta(1 - 4\beta k^2)} - \frac{[2\beta k(kL - 1) - L](\alpha_m^{NC*} + \alpha_r^{NC*})}{\beta(1 - 4\beta k^2)} \right] \cdot \left[\frac{(2\beta k^2 - 1)(a - \beta t)}{4\beta k^2 - 1} + \frac{(2\beta k^2 L - L - 2k\beta)(\alpha_m^{NC*} + \alpha_r^{NC*})}{4\beta k^2 - 1} \right] \\
&\quad + \frac{(a - \beta t)(4\beta k^2 - 3) + [L(4\beta k^2 - 3) - 8\beta k](\alpha_m^{NC*} + \alpha_r^{NC*})}{2\beta k(1 - 4\beta k^2)} \alpha_r^{NC*} - \frac{1}{2} (\alpha_r^{NC*})^2 \\
\alpha_m^{NC*} &= \frac{4k(a - t\beta)(1 - 2\beta k^2)(L - 2\beta k^2 L + 2\beta k) \left[(3L - a + \beta t)(4\beta k^2 - 3) - 2\beta k(13 - 4\beta k^2) \right] \\
&\quad + (a - \beta t)(1 - 4\beta k^2) \left[9L + 30\beta k + 64\beta^3 k^5 - 80\beta^2 k^3 - 16\beta k^2 L(2 + 2\beta^2 k^4 - 3\beta k^2) \right]}{\left[12k(a - t\beta)(1 - 2\beta k^2)(L - 2\beta k^2 L + 2\beta k) + (12\beta k^2 L - 9L - 26\beta k + 8\beta^2 k^3)(1 - 4\beta k^2) \right]} \\
&\quad \cdot \left[2\beta k(5 - 4\beta k^2) - (4\beta k^2 - 3)L \right] \\
\alpha_r^{NC*} &= \frac{4k(a - t\beta)(a - \beta t)(4\beta k^2 - 3)(1 - 2\beta k^2)(L - 2\beta k^2 L + 2\beta k) \\
&\quad + (a - \beta t)(1 - 4\beta k^2) \left[9L + 30\beta k + 64\beta^3 k^5 - 80\beta^2 k^3 - 16\beta k^2 L(2 + 2\beta^2 k^4 - 3\beta k^2) \right]}{\left[12k(a - t\beta)(1 - 2\beta k^2)(L - 2\beta k^2 L + 2\beta k) + (12\beta k^2 L - 9L - 26\beta k + 8\beta^2 k^3)(1 - 4\beta k^2) \right]} \\
&\quad \cdot \left[2\beta k(5 - 4\beta k^2) - (4\beta k^2 - 3)L \right]
\end{aligned}$$

Appendix A.2. Proof of the CN Model

This section presents the optimal decision variables and performance indicators under the CN model, including carbon reduction levels, carbon tax rate, pricing decisions, market demand, and profits of both the supply chain and the government.

$$\begin{aligned}
\alpha_m^{CN*} &= \alpha_r^{CN*} = \frac{(\beta t - a) [12kL(2\beta k^2 - 1)^2 - 64\beta^2 k^4 + 40\beta k^2 - 3]}{24k(2\beta k^2 L - L - 2k\beta)^2 + (1 - 4\beta k^2) [4L(4\beta k^2 - 3) - 2\beta k(17 - 4\beta k^2)]} \\
e_{SC}^{CN*} &= \frac{2k(2\beta k^2 - 1)a + 2k(2\beta k^2 L - L - 2k\beta)(\alpha_m^{CN*} + \alpha_r^{CN*}) - 2k\beta t(2\beta k^2 - 1)}{4\beta k^2 - 1} - (\alpha_m^{CN*} + \alpha_r^{CN*}) \\
\theta^{CN*} &= \frac{(a - \beta t)(4\beta k^2 - 3) + [L(4\beta k^2 - 3) - 8\beta k](\alpha_m^{CN*} + \alpha_r^{CN*})}{2\beta k(1 - 4\beta k^2)} \\
\omega^{CN*} &= \frac{a + L(\alpha_m^{CN*} + \alpha_r^{CN*}) + t\beta}{2\beta} \\
p^{CN*} &= \frac{2k^2 a + 2k(kL + 1)(\alpha_m^{CN*} + \alpha_r^{CN*}) + (2\beta k^2 - 1)t}{4\beta k^2 - 1} \\
Q^{CN*} &= \frac{(2\beta k^2 - 1)(a - \beta t) + (2\beta k^2 L - L - 2k\beta)(\alpha_m^{CN*} + \alpha_r^{CN*})}{4\beta k^2 - 1} \\
\pi_G^{CN*} &= (p - t - 2k^2 Q^{CN*}) Q^{CN*} + \frac{(Q^{CN*})^2}{2\beta} + \left[2k Q^{CN*} - (\alpha_m^{CN*} + \alpha_r^{CN*}) \right] (\alpha_m^{CN*} + \alpha_r^{CN*}) + \alpha_m^{CN*} \cdot \alpha_r^{CN*} \\
\pi_{M+R}^{CN*} &= \left[\frac{3(a - \beta t)(1 - 2\beta k^2)}{\beta(1 - 4\beta k^2)} - \frac{3(2\beta k^2 L - L - 2\beta k)(\alpha_m^{CN*} + \alpha_r^{CN*})}{\beta(1 - 4\beta k^2)} \right] \cdot \left[\frac{(1 - 2\beta k^2)(a - \beta t)}{1 - 4\beta k^2} + \frac{(2\beta k^2 L - L - 2k\beta)(\alpha_m^{CN*} + \alpha_r^{CN*})}{4\beta k^2 - 1} \right] \\
&\quad + \frac{(a - \beta t)(4\beta k^2 - 3)(\alpha_m^{CN*} + \alpha_r^{CN*}) + [L(4\beta k^2 - 3) - 8\beta k](\alpha_m^{CN*} + \alpha_r^{CN*})^2}{2\beta k(1 - 4\beta k^2)} - \frac{1}{2} \left[(\alpha_m^{CN*})^2 + (\alpha_r^{CN*})^2 \right]
\end{aligned}$$

Appendix A.3. Proof of the NN Model

The profit functions in the NN model are given as follows.

For the manufacturer, the profit maximization problem is:

$$\begin{aligned} \max_{\alpha_m} \pi_M^{NN} = & \frac{[2\beta(\omega - t)(1 + 4\beta k^2) - (4\beta k^2 - 1)(a - \beta t)]}{2\beta(1 + 4\beta k^2)} \\ & + \frac{[4\beta k - (4\beta k^2 - 1)L](\alpha_m + \alpha_r)}{2\beta(1 + 4\beta k^2)} \\ & \times \left[\frac{(a - \beta t)}{1 + 4\beta k^2} + \frac{(L + 2\beta k)(\alpha_m + \alpha_r)}{1 + 4\beta k^2} \right] \\ & + \frac{(4\beta k^2 - 1)[a + L(\alpha_m + \alpha_r) - \beta t]\alpha_m - 4\beta k(\alpha_m + \alpha_r)\alpha_m}{2\beta k(1 + 4\beta k^2)} - \frac{1}{2}\alpha_m^2 \end{aligned}$$

For the retailer, the profit maximization problem is:

$$\begin{aligned} \max_{\alpha_r} \pi_R^{NN} = & \frac{[2\beta(\omega - t)(1 + 4\beta k^2) - (4\beta k^2 - 1)(a - \beta t) + [4\beta k - (4\beta k^2 - 1)L](\alpha_m + \alpha_r)]}{2\beta(1 + 4\beta k^2)} \\ & \times \left[\frac{(a + (L + 2\beta k)(\alpha_m + \alpha_r) - \beta t)}{1 + 4\beta k^2} \right] \\ & + \frac{(4\beta k^2 - 1)[a + L(\alpha_m + \alpha_r) - \beta t] - 4\beta k(\alpha_m + \alpha_r)}{2\beta k(1 + 4\beta k^2)} \alpha_r - \frac{1}{2}\alpha_r^2 \end{aligned}$$

In the NN model, the optimal carbon emission reduction levels, carbon tax rate, sales price, market demand, joint profit of the manufacturer and retailer, and government profit are given as follows:

$$\alpha_m^{NN*} = \alpha_r^{NN*} = \frac{2\beta k(\omega - t)(1 + 4\beta k^2)(L + 2\beta k) + 2k(a - \beta t)[2\beta k - (4\beta k^2 - 1)(L + \beta k)]}{4k(L + 2\beta k)[(4\beta k^2 - 1)L - 4\beta k] + (1 + 4\beta k^2)[2\beta k(7 + 4\beta k^2) - 3(4\beta k^2 - 1)(a - \beta t + L)]}$$

$$e_{SC}^{NN*} = \frac{2k(a - \beta t) + (2kL - 1)(\alpha_m^{NN*} + \alpha_r^{NN*})}{1 + 4\beta k^2} - (\alpha_m^{NN*} + \alpha_r^{NN*})$$

$$\theta^{NN*} = \frac{(4\beta k^2 - 1)[a + L(\alpha_m^{NN*} + \alpha_r^{NN*}) - \beta t] - 4\beta k(\alpha_m^{NN*} + \alpha_r^{NN*})}{2\beta k(1 + 4\beta k^2)}$$

$$\omega^{NN*} = \frac{a + L(\alpha_m^{NN*} + \alpha_r^{NN*}) + t\beta}{2\beta}$$

$$p^{NN*} = \frac{4k^2[a + L(\alpha_m^{NN*} + \alpha_r^{NN*})] + t - 2k(\alpha_m^{NN*} + \alpha_r^{NN*})}{1 + 4\beta k^2}$$

$$Q^{NN*} = \frac{a + (L + 2\beta k)(\alpha_m^{NN*} + \alpha_r^{NN*}) - \beta t}{1 + 4\beta k^2}$$

$$\begin{aligned} \pi_{M+R}^{NN*} = & \left[\frac{3(a - \beta t)(1 - 2\beta k^2)}{\beta(1 - 4\beta k^2)} - \frac{3(2\beta k^2 L - L - 2\beta k)(\alpha_m^{NN*} + \alpha_r^{NN*})}{\beta(1 - 4\beta k^2)} \right] \cdot \left[\frac{(1 - 2\beta k^2)(a - \beta t)}{1 - 4\beta k^2} + \frac{(2\beta k^2 L - L - 2\beta k)(\alpha_m^{NN*} + \alpha_r^{NN*})}{4\beta k^2 - 1} \right] \\ & + \frac{(a - \beta t)(4\beta k^2 - 3)(\alpha_m^{NN*} + \alpha_r^{NN*}) + [L(4\beta k^2 - 3) - 8\beta k](\alpha_m^{NN*} + \alpha_r^{NN*})^2}{2\beta k(1 + 4\beta k^2)} - \frac{1}{2}[(\alpha_m^{NN*})^2 + (\alpha_r^{NN*})^2] \end{aligned}$$

$$\pi_G^{NN*} = \frac{(4\beta k^2 L + L - 2\beta k - 8\beta^2 k^3)(\alpha_m^{NN*} + \alpha_r^{NN*}) + (a - \beta t)(1 + 4\beta k^2)}{2\beta(1 + 4\beta k^2)} \cdot \frac{a + (L + 2\beta k)(\alpha_m^{NN*} + \alpha_r^{NN*}) - \beta t}{1 + 4\beta k^2} \\ + \frac{k(a - \beta t)(\alpha_m^{NN*} + \alpha_r^{NN*}) + (kL - 1 - 2\beta k^2)(\alpha_m^{NN*} + \alpha_r^{NN*})^2}{1 + 4\beta k^2} - \frac{1}{2}[(\alpha_m^{NN*})^2 + (\alpha_r^{NN*})^2]$$

Appendix A.4. Proof of the OO Model

In the OO model, the optimal carbon emission reduction levels, carbon tax rate, wholesale price, market demand, and the joint profit of the manufacturer and retailer, as well as the government profit, are given as follows:

$$\alpha_m^{OO*} = \alpha_r^{OO*} = \frac{(a - \beta t)[6k(L + 2\beta k) + 8\beta k^3(L + 4\beta k) - 1]}{4[2k\beta(3 + 4\beta k^2)(1 + 4\beta k^2) + L(1 - 4\beta k^2)(1 + 4\beta k^2) - k(3 + 4\beta k^2)(L + 2\beta k)^2]} \\ e_{SC}^{OO*} = \frac{2k(a - \beta t) + (2kL - 1)(\alpha_m^{OO*} + \alpha_r^{OO*})}{(1 + 4\beta k^2)} \\ p^{OO*} = \frac{4k^2 a + 2k(2kL - 1)(\alpha_m^{OO*} + \alpha_r^{OO*}) + t}{(1 + 4\beta k^2)} \\ \theta^{OO*} = \frac{(\beta t - a)(1 - 4\beta k^2) - (L + 4\beta k - 4\beta k^2 L)(\alpha_m^{OO*} + \alpha_r^{OO*})}{2k\beta(1 + 4\beta k^2)} \\ Q^{OO*} = \frac{a + (\alpha_m^{OO*} + \alpha_r^{OO*})(L + 2\beta k) - \beta t}{(1 + 4\beta k^2)} \\ \pi_{SC}^{OO*} = \frac{(3 + 4\beta k^2)}{2\beta(1 + 4\beta k^2)^2} [a + (L + 2\beta k)(\alpha_m^{OO*} + \alpha_r^{OO*}) - \beta t]^2 \\ + \frac{(\beta t - a)(1 - 4\beta k^2)(\alpha_m^{OO*} + \alpha_r^{OO*})}{2k\beta(1 + 4\beta k^2)} \\ + \frac{[(4\beta k^2 - 1)L - k\beta(7 + 12\beta k^2)]}{2k\beta(1 + 4\beta k^2)} (\alpha_m^{OO*} + \alpha_r^{OO*})^2 \\ + 2\alpha_m^{OO*} \alpha_r^{OO*}$$

Appendix A.5. Proof of Proposition 1

Let the total emission-reduction effort be denoted as

$$\alpha = \alpha_m^{NC*} + \alpha_r^{NC*}.$$

In the NC model, define emission intensity as

$$EI_{SC}^{NC*} = \frac{e_{SC}^{NC*}}{Q^{NC*}},$$

where

$$e_{SC}^{NC*} = 2kQ^{NC*} - \alpha$$

and

$$Q^{NC*} = \frac{(2\beta k^2 - 1)(a - \beta t) + (2\beta k^2 L - L - 2k\beta)\alpha}{4\beta k^2 - 1}.$$

Substituting into EI_{SC}^{NC*} , we obtain

$$EI_{SC}^{NC*} = \frac{2kQ^{NC*} - \alpha}{Q^{NC*}} = 2k - \frac{\alpha}{Q^{NC*}}.$$

Further substituting Q^{NC*} yields

$$EI_{SC}^{NC*} = 2k - \frac{(4\beta k^2 - 1)\alpha}{(2\beta k^2 - 1)(a - \beta t) + (2\beta k^2 L - L - 2k\beta)\alpha}.$$

Taking the derivative of EI_{SC}^{NC*} with respect to α , we obtain

$$\frac{\partial EI_{SC}^{NC*}}{\partial \alpha} = - \frac{(4\beta k^2 - 1)(2\beta k^2 - 1)(a - \beta t)}{[(2\beta k^2 - 1)(a - \beta t) + (2\beta k^2 L - L - 2k\beta)\alpha]^2}.$$

When $a - \beta t > 0$ and $\frac{1}{2} < \beta k^2 < \frac{3}{4}$, we have

$$4\beta k^2 - 1 > 0, \quad 2\beta k^2 - 1 > 0,$$

and therefore

$$\frac{\partial EI_{SC}^{NC*}}{\partial \alpha} < 0.$$

Hence, the emission intensity decreases as the total emission-reduction effort increases.

Appendix A.6. Proof of Proposition 2

We analyze the marginal effects of α on the following variables:

- Carbon tax rate:

$$\theta^{NC*} = \frac{(a - \beta t)(4\beta k^2 - 3) + [L(4\beta k^2 - 3) - 8\beta k]\alpha}{2\beta k(1 - 4\beta k^2)} \Rightarrow \frac{\partial \theta^{NC*}}{\partial \alpha} = \frac{(4\beta k^2 - 3)L - 8\beta k}{2\beta k(1 - 4\beta k^2)}$$

- Wholesale price:

$$\omega^{NC*} = \frac{a + L\alpha + \beta t}{2\beta} \Rightarrow \frac{\partial \omega^{NC*}}{\partial \alpha} = \frac{L}{2\beta}$$

- Market price:

$$p^{NC*} = \frac{2k^2 a + 2k(kL + 1)\alpha + (2\beta k^2 - 1)t}{4\beta k^2 - 1} \Rightarrow \frac{\partial p^{NC*}}{\partial \alpha} = \frac{2k(kL + 1)}{4\beta k^2 - 1}$$

- Market demand:

$$Q^{NC*} = \frac{(2\beta k^2 - 1)(a - \beta t) + (2\beta k^2 L - L - 2k\beta)\alpha}{4\beta k^2 - 1} \Rightarrow \frac{\partial Q^{NC*}}{\partial \alpha} = \frac{2\beta k^2 L - L - 2\beta k}{4\beta k^2 - 1}$$

Therefore, these results establish the comparative statics reported in Proposition 2.

Appendix A.7. Proof of Proposition 3

Let the total emission-reduction effort in the CN model be denoted as

$$\alpha = \alpha_m^{CN*} + \alpha_r^{CN*}.$$

In the CN model, define emission intensity as

$$EI_{SC}^{CN*} = \frac{e_{SC}^{CN*}}{Q^{CN*}},$$

where

$$e_{SC}^{CN*} = 2kQ^{CN*} - \alpha$$

and

$$Q^{CN*} = \frac{(2\beta k^2 - 1)(a - \beta t) + (2\beta k^2 L - L - 2k\beta)\alpha}{4\beta k^2 - 1}.$$

Substituting into EI_{SC}^{CN*} , we obtain

$$EI_{SC}^{CN*} = \frac{2kQ^{CN*} - \alpha}{Q^{CN*}} = 2k - \frac{\alpha}{Q^{CN*}}.$$

Further substituting Q^{CN*} yields

$$EI_{SC}^{CN*} = 2k - \frac{(4\beta k^2 - 1)\alpha}{(2\beta k^2 - 1)(a - \beta t) + (2\beta k^2 L - L - 2k\beta)\alpha}.$$

Taking the derivative of EI_{SC}^{CN*} with respect to α , we obtain

$$\frac{\partial EI_{SC}^{CN*}}{\partial \alpha} = - \frac{(4\beta k^2 - 1)(2\beta k^2 - 1)(a - \beta t)}{[(2\beta k^2 - 1)(a - \beta t) + (2\beta k^2 L - L - 2k\beta)\alpha]^2}.$$

When $a - \beta t > 0$ and $\frac{1}{2} < \beta k^2 < \frac{3}{4}$, we have

$$\frac{\partial EI_{SC}^{CN*}}{\partial \alpha} < 0.$$

Hence, the emission intensity decreases as the total emission-reduction effort increases.

Appendix A.8. Proof of Proposition 4

Let

$$\alpha = \alpha_m^{CN*} + \alpha_r^{CN*}.$$

The optimal carbon tax rate is

$$\theta^{CN*} = \frac{(a - \beta t)(4\beta k^2 - 3) + [L(4\beta k^2 - 3) - 8\beta k]\alpha}{2\beta k(1 - 4\beta k^2)}.$$

Taking the derivative with respect to α , we obtain

$$\frac{\partial \theta^{CN*}}{\partial \alpha} = \frac{(4\beta k^2 - 3)L - 8\beta k}{2\beta k(1 - 4\beta k^2)}.$$

When $\frac{1}{2} < \beta k^2 < \frac{3}{4}$, we have

$$4\beta k^2 - 3 < 0, \quad 1 - 4\beta k^2 < 0.$$

Since $L > 0$, $\beta > 0$, and $k > 0$, the numerator $(4\beta k^2 - 3)L - 8\beta k$ is negative, and the denominator $2\beta k(1 - 4\beta k^2)$ is also negative. Therefore,

$$\frac{\partial \theta^{CN*}}{\partial \alpha} > 0.$$

The optimal wholesale price is

$$\omega^{CN*} = \frac{a + L\alpha + t\beta}{2\beta},$$

thus

$$\frac{\partial \omega^{CN*}}{\partial \alpha} = \frac{L}{2\beta} > 0.$$

The optimal retail price is

$$p^{CN*} = \frac{2k^2a + 2k(kL + 1)\alpha + (2\beta k^2 - 1)t}{4\beta k^2 - 1},$$

thus

$$\frac{\partial p^{CN*}}{\partial \alpha} = \frac{2k(kL + 1)}{4\beta k^2 - 1} > 0.$$

These results establish the comparative statics reported in Proposition 4.

In the NN model, let $\alpha = \alpha_m^{NN*} + \alpha_r^{NN*}$.

Appendix A.9. Proof of Proposition 5

In the NN model, define emission intensity as $EI_{SC}^{NN*} = \frac{e_{SC}^{NN*}}{Q^{NN*}}$, where $e_{SC}^{NN*} = 2kQ^{NN*} - \alpha$ and $Q^{NN*} = \frac{a + (L + 2\beta k)\alpha - \beta t}{1 + 4\beta k^2}$.

Substituting into EI_{SC}^{NN*} , we obtain $EI_{SC}^{NN*} = \frac{2kQ^{NN*} - \alpha}{Q^{NN*}} = 2k - \frac{\alpha}{Q^{NN*}}$. Further substituting Q^{NN*} yields $EI_{SC}^{NN*} = 2k - \frac{(1 + 4\beta k^2)\alpha}{a + (L + 2\beta k)\alpha - \beta t}$.

Taking the derivative of EI_{SC}^{NN*} with respect to α , we obtain

$$\frac{\partial EI_{SC}^{NN*}}{\partial \alpha} = -\frac{(1 + 4\beta k^2)(a - \beta t)}{[a + (L + 2\beta k)\alpha - \beta t]^2}.$$

When $a - \beta t > 0$, we have

$$\frac{\partial EI_{SC}^{NN*}}{\partial \alpha} < 0.$$

Hence, the emission intensity decreases as the total emission-reduction effort increases.

Appendix A.10. Proof of Proposition 6

Carbon tax rate:

$$\theta^{NN*} = \frac{(4\beta k^2 - 1)[a + L\alpha - \beta t] - 4\beta k\alpha}{2\beta k(1 + 4\beta k^2)},$$

thus

$$\frac{\partial \theta^{NN*}}{\partial \alpha} = \frac{(4\beta k^2 - 1)L - 4\beta k}{2\beta k(1 + 4\beta k^2)}.$$

When

$$L > \frac{4\beta k}{4\beta k^2 - 1},$$

we have

$$\frac{\partial \theta^{NN*}}{\partial \alpha} > 0.$$

Retail price:

$$p^{NN*} = \frac{4k^2(a + L\alpha) + t - 2k\alpha}{1 + 4\beta k^2},$$

thus

$$\frac{\partial p^{NN*}}{\partial \alpha} = \frac{4k^2L - 2k}{1 + 4\beta k^2}.$$

When

$$L > \frac{1}{2k},$$

we have

$$\frac{\partial p^{NN*}}{\partial \alpha} > 0.$$

Market demand:

$$Q^{NN*} = \frac{a + (L + 2\beta k)\alpha - \beta t}{1 + 4\beta k^2},$$

thus

$$\frac{\partial Q^{NN*}}{\partial \alpha} = \frac{L + 2\beta k}{1 + 4\beta k^2} > 0.$$

Under the stronger condition

$$L > \frac{4\beta k}{4\beta k^2 - 1} \quad \text{and} \quad \frac{1}{2} < \beta k^2 < \frac{3}{4},$$

the carbon tax rate and retail price both increase with the rise in emission-reduction effort, while market demand always increases.

Appendix A.11. Proof of Proposition 7

Let

$$\alpha = \alpha_m^{OO*} + \alpha_r^{OO*}.$$

Define emission intensity as

$$EI_{SC}^{OO*} = \frac{e_{SC}^{OO*}}{Q^{OO*}},$$

where

$$e_{SC}^{OO*} = 2kQ^{OO*} - \alpha, \quad Q^{OO*} = \frac{a + (L + 2\beta k)\alpha - \beta t}{1 + 4\beta k^2}.$$

Thus,

$$EI_{SC}^{OO*} = 2k - \frac{(1 + 4\beta k^2)\alpha}{a + (L + 2\beta k)\alpha - \beta t}.$$

Taking the derivative with respect to α , we obtain

$$\frac{\partial EI_{SC}^{OO*}}{\partial \alpha} = -\frac{(1 + 4\beta k^2)(a - \beta t)}{[a + (L + 2\beta k)\alpha - \beta t]^2} < 0.$$

Hence, the emission intensity decreases as the total emission-reduction effort increases.

Appendix A.12. Proof of Proposition 8

For the retail price,

$$\frac{\partial p^{OO*}}{\partial \alpha} = \frac{2k(2kL - 1)}{1 + 4\beta k^2}.$$

For the carbon tax rate,

$$\frac{\partial \theta^{OO*}}{\partial \alpha} = \frac{-(L + 4\beta k - 4\beta k^2 L)}{2k\beta(1 + 4\beta k^2)}.$$

For market demand,

$$\frac{\partial Q^{OO*}}{\partial \alpha} = \frac{L + 2\beta k}{1 + 4\beta k^2} > 0.$$

Therefore, p^{OO*} increases with the total emission-reduction effort when $L > \frac{1}{2k}$, θ^{OO*} increases with the total emission-reduction effort when $L > \frac{4\beta k}{4\beta k^2 - 1}$, and Q^{OO*} always increases with the total emission-reduction effort.

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