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Cross-border Low-Carbon Supply Chain Decision-Making Considering Vertical Spillover and Blockchain under CBAM Regulation

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Abstract. Against the background of the global "dual carbon" goal and the EU Carbon Border Adjustment Mechanism (CBAM), targeting problems such as missing trust in emission reduction and insufficient technological collaboration in cross-border low-carbon supply chains, this paper incorporates blockchain technology, vertical spillover of emission reduction and consumer low-carbon preference into a unified analytical framework. It constructs a two-echelon cross-border supply chain model consisting of a single supplier and a single manufacturer, builds Stackelberg game models under centralized decision-making and decentralized decision-making respectively, comparatively analyzes the optimal emission reduction levels, pricing strategies and profit distributions under two scenarios with and without vertical spillover, and verifies the conclusions through numerical simulation. The research shows that the EU CBAM carbon tax, vertical spillover of emission reduction and consumer low-carbon preference form a positive synergistic incentive, which significantly lifts the supply chain's emission reduction level and overall profit, and the synergistic effect is more prominent under centralized decision-making. A rising emission reduction cost coefficient will restrain enterprises' investment in emission reduction, and vertical spillover will aggravate this restraining effect. Whether vertical spillover is considered or not, centralized decision-making outperforms decentralized decision-making in both emission reduction efficiency and total supply chain profit; the higher the carbon tax rate and vertical spillover rate, the wider the gap between the two. This paper further puts forward management insights from the aspects of enterprise technology sharing, decision-making mode selection and government policy guidance, so as to provide theoretical reference and decision support for cross-border supply chains to respond to CBAM regulations and realize low-carbon transformation.

Keywords: CBAM, low-carbon supply chain, vertical spillover, blockchain, emission reduction decision-making

1. Introduction

Driven by the global "dual carbon" goal, supply chain emission reduction is faced with trust dilemmas. Blockchain enables full traceability of emission reduction and breaks the trust bottleneck;

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upstream and downstream technology spillover and policy guidance jointly accelerate the diffusion of emission reduction technologies and improve the performance of the whole chain. At present, the impact of vertical spillover on enterprise emission reduction, the interaction between consumer trust and blockchain pricing decisions, and their combined effects on supply chain profit and consumer surplus remain key issues yet to be clarified. This study makes a preliminary exploration of using blockchain technology to solve supply chain emission reduction problems under the "dual carbon" background, and holds certain reference value.

As an innovative digital tool that empowers supply chain optimization, blockchain technology has irreplaceable practical value and application potential in improving information transparency and solving information asymmetry, and has drawn wide attention from academia. Research on blockchain technology mainly focuses on two aspects: First, the paths for blockchain technology to solve common problems in supply chains. Zhang et al. [1] studied the impact of blockchain technology on emission reduction decisions in dual-product low-carbon supply chains, and analyzed how factors such as technology investment affect enterprise profits. Xiao et al. [2] identified the influence of blockchain technology on the carbon emission reduction strategies of supply chain members, and focused on its role in curbing manufacturers' misreporting behavior and raising emission reduction levels. Sun et al. [3] demonstrated the impact of blockchain technology on the dynamic responsiveness of supply chain systems, and quantified its effect on improving inventory stability. Based on the resource-based view and transaction cost theory, Li and Fu [4] studied how blockchain technology application affects supply chain performance through supply chain process integration, and verified the mediating role of information flow, logistics and capital flow integration. Lou et al. [5] confirmed the impact of blockchain technology on supply chain finance, and analyzed its mechanism in easing financing constraints and improving capital availability through a tripartite game and dynamic evolutionary game model. Zhang et al. [6] established the realization path of blockchain-empowered supply chain quality visibility, pointed out the existing information security dilemmas, and provided technical support ideas for supply chain quality control. Ji et al. [7] built a product pricing game model with blockchain participation decisions, and explored its influence on the pricing mechanism of retail supply chains. Second, targeted application value of blockchain technology in specific industries. Tan et al. [8] analyzed the application value of blockchain technology in agricultural product supply chains in terms of cutting transaction costs and ensuring food safety. Focusing on the particularity of vaccine supply chains, Tan et al. [9] constructed a pricing strategy model based on blockchain technology, providing solutions for vaccine traceability, anti-counterfeiting and symmetric information transmission. Combined with the features of the O2O model, Tan and Zeng [10] analyzed the two-stage pricing logic of fresh agricultural product supply chains supported by blockchain technology, helping to balance product circulation efficiency and market competitiveness. Aiming at the pain points of contract farming supply chains, Wang and Zhang [11] studied the introduction path and implementation strategy of blockchain traceability technology, providing theoretical reference for ensuring credible agricultural product traceability and optimizing supply chain collaboration.

As an important carrier of technology dissemination and knowledge sharing between upstream and downstream enterprises in the supply chain, vertical spillover technology can optimize enterprise emission reduction decisions and lower collaborative emission reduction costs through technology diffusion and other channels, playing a key supporting role in improving the carbon emission reduction efficiency of the supply chain. Song and Zhang [12] explored the low-carbon spillover effect of government green procurement in corporate supply chain networks, and found that it can significantly promote carbon emission reduction of upstream suppliers through three

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mechanisms: product demand expansion, green technology spillover and cooperation maintenance pressure. The effect only works on first-tier suppliers and has no significant impact on downstream customers, and the nature of enterprise property rights and suppliers' export behavior will affect the spillover effect. Yu and Wei [13] built a supply chain game model with two manufacturers and one single retailer, and concluded that manufacturers should choose R&D competition or cooperation under different combinations of spillover rate and preference degree, providing a basis for horizontal R&D decisions in supply chains. Yang and Zhang [14] empirically tested the low-carbon spillover effect of digital enterprises' OFDI on the downstream of the supply chain, and confirmed that it drives downstream carbon emission reduction through three channels: "innovation chain", "capital chain" and "information chain". Jiang and Sun [15] studied the impacts of two-way technology spillover and carbon transfer on supply chain carbon emission reduction, and found that vertical technology spillover improves emission reduction level while carbon transfer and horizontal technology spillover play an inhibitory role, and changes in power structure will alter the influence intensity of each factor. Taking the environmental pollution liability insurance pilot as a quasi-natural experiment, Zhang et al. [16] adopted the staggered difference-in-differences model and found that the policy pilot significantly suppressed downstream carbon emission intensity. Li and Yi [17] established a two-echelon supply chain model with one supplier and one manufacturer, analyzed how vertical spillover affects emission reduction decisions and profits under centralized and decentralized decision-making, and found that a higher vertical spillover rate can reduce prices and raise emission reduction effort levels and profits. From the perspective of competition strategy, Tang and Xiao [18] analyzed the relationship between technology spillover, energy conservation & emission reduction and social welfare through dynamic game analysis of coal power enterprises, and revealed the mechanism of technology spillover in emission reduction of the power industry. Focusing on the agricultural field, Tian and Yin [19] tested the impact of technological progress on agricultural energy carbon emission reduction, and discussed the moderating role of rebound effect and spatial spillover effect, providing reference for low-carbon agricultural development. Wu et al. [20] studied the carbon emission reduction effect of technological progress in animal husbandry, and analyzed the internal mechanism of technological progress in promoting animal husbandry carbon emission reduction through tests of mediating, moderating and spatial spillover effects. From the perspective of strategic interaction and technology spillover, He et al. [21] analyzed the regional correlation characteristics of agricultural carbon emission reduction, providing theoretical support for regional coordinated promotion of agricultural carbon reduction. Yan et al. [22] explored how ESG green spillover affects corporate green innovation through supply chain transmission, confirmed the supply chain transmission effect of ESG performance, and provided a new perspective for enterprises to promote green innovation through ESG development.

Supply chain emission reduction decision is the core link to achieve the "dual carbon" goal and optimize the ecological and economic benefits of the supply chain. Xia et al. [23] focused on carbon trading regulations and consumer overconfidence, built a two-echelon supply chain model consisting of one manufacturer and one retailer with presale options, analyzed the impacts of retailer presale strategies and consumer overconfidence on game equilibrium, profits and carbon emissions, and clarified the optimal sales mode selection under different wholesale price ranges. Aiming at the CCER voluntary emission reduction trading mechanism, Wei et al. [24] constructed a three-stage supply chain emission reduction game model, and revealed how CCER trading price and purchase limit coefficient affect enterprise emission reduction decisions. Under the background of carbon tax policy and consumer low-carbon preference, Yang and Luo [25] explored carbon emission reduction decisions under wholesale price contracts and revenue sharing contracts with stochastic demand, and

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identified the optimal emission reduction rate that maximizes the revenue of manufacturers and the whole supply chain under the two contracts. Combined with carbon quota trading policy and the development trend of e-commerce, Zhang et al. [26] built three decision models: single offline channel emission reduction, dual-channel no emission reduction and dual-channel emission reduction, analyzed the combined effects of carbon quota, carbon trading price and consumer low-carbon preference, and solved the optimal emission reduction effort. Focusing on the EU CBAM, Zhao and Tang [27] compared the optimal emission reduction levels and pricing strategies under three scenarios: no CBAM implementation, emission reduction only by manufacturers in CBAM regions, and emission reduction by both parties, and analyzed the impact of CBAM on supply chain members' profits and the formation of "green trade barriers". For dual-channel low-carbon supply chains, Huang et al. [28] established Stackelberg game models under decentralized and centralized decision-making, analyzed how different modes affect manufacturers' emission reduction efforts, and verified the coordination advantage of the cost-sharing mode.

2. Basic assumptions

Consider a two-echelon cross-border low-carbon supply chain composed of one leading supplier and one following manufacturer. The supply chain exports products to the EU market and must strictly comply with EU CBAM carbon tax regulations; both the supplier and the manufacturer carry out emission reduction technology R&D, and the R&D results produce positive vertical spillover effects; EU consumers have notable low-carbon preferences, and market demand is jointly affected by low-carbon preference, product price and the overall emission reduction level of the supply chain. The assumptions are as follows:

(1) The independent emission reduction level of the supplier is e_S, the independent emission reduction level of the manufacturer is e_M, and the vertical spillover rate of supply chain emission reduction is $\eta(0 < \eta < 1)$, which represents the proportion of one party's emission reduction technology results utilized by the other party, and the spillover coefficients of upstream and downstream enterprises are identical. When vertical spillover is considered, the effective emission reduction level of the supplier is $e_S + \eta e_M$, and the effective emission reduction level of the manufacturer is $e_M + \eta e_S$; when vertical spillover is not considered, $\eta = 0$, and the effective emission reduction levels of both parties equal their independent emission reduction levels.

(2) The supplier is the main source of carbon emissions in the supply chain. The benchmark marginal carbon emission per unit of intermediate product is e_0 (consistent with EU CBAM carbon emission accounting standards), and the actual carbon emission per unit product decreases linearly with the rise of effective emission reduction level. When vertical spillover is considered, the actual carbon emission is $e_0 - (e_S + \eta e_M)$; when vertical spillover is not considered, it is $e_0 - e_S$, and $e_0 > e_S + \eta e_M$ holds to ensure positive actual carbon emission. The supply chain pays CBAM carbon tax to the EU based on the actual carbon emission per unit product, with a carbon tax rate of t (yuan per unit carbon emission), which is uniformly paid by the supplier and fully included in its own cost accounting.

(3) Market demand is affected by potential demand scale, product retail price p, consumer low-carbon preference coefficient $\gamma(\gamma > 0)$ and the overall emission reduction level of the supply chain: when vertical spillover is not considered, the market demand function is $Q = 1 - p + \gamma(e_S + e_M)$; when vertical spillover is considered, the superposition of upstream and downstream emission reduction results enhances the low-carbon effect, and the market demand function is $Q = 1 - p + \gamma(1 + \eta)(e_S + e_M)$.

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(4) Emission reduction R&D cost has a quadratic relationship with the independent emission reduction level [29]. The emission reduction cost coefficients of both the supplier and the manufacturer are k, so the supplier's emission reduction cost is $\frac{1}{2}ke_S^2$, and the manufacturer's emission reduction cost is $\frac{1}{2}ke_M^2$.

(5) The marginal production cost of the supplier's intermediate product is c, which is sold to the manufacturer at the wholesale price w; the manufacturer bears no additional cost for processing the intermediate product, and sells the final product to EU consumers at the retail price p, with $p > w > c$ to ensure reasonable profit margins for all supply chain entities.

(6) To ensure the practical economic significance of the model equilibrium solution: the emission reduction cost coefficient satisfies $k > 4(\gamma + e_0 t)^2$ to prevent unrestricted emission reduction R&D investment by enterprises [30]; market demand $Q > 0$ to ensure the practical value of production and operation; the carbon tax rate t, low-carbon preference coefficient γ and vertical spillover rate η all fall within reasonable ranges.

3. Emission reduction decisions without vertical spillover effect

Enterprises adopt full protection measures for emission reduction R&D technologies, so that upstream and downstream emission reduction technologies in the supply chain cannot spill over to each other ($\eta = 0$). The supplier's effective emission reduction level is e_S, and the actual carbon emission is $e_0 - e_S$. This section constructs centralized and decentralized decision-making models respectively, and analyzes the optimal emission reduction and pricing strategies of the supply chain under EU CBAM carbon tax regulation.

3.1. Centralized decision-making

Under centralized decision-making, the supplier and the manufacturer break interest barriers, jointly decide the supplier's emission reduction level e_S, the manufacturer's emission reduction level e_M and the product retail price p with the goal of maximizing overall supply chain profit, and eliminate the "double marginalization effect" of decentralized decision-making. The overall supply chain profit equals final product sales revenue minus production cost, carbon tax cost and emission reduction R&D costs of both parties. The supply chain profit function is:

$$\pi_{SCC} = (p - c)Q - t(e_0 - e_S)Q - \frac{1}{2}ke_S^2 - \frac{1}{2}ke_M^2 \tag{1}$$

Substitute the demand function without vertical spillover $Q = 1 - p + \gamma(e_S + e_M)$ into the above formula:

$$\pi_{SCC} = (p - c - te_0 + te_S)\left[1 - p + \gamma(e_S + e_M)\right] - \frac{1}{2}ke_S^2 - \frac{1}{2}ke_M^2 \tag{2}$$

Lemma 1 When vertical spillover effect is not considered, there exists a unique optimal emission reduction level and retail price in the supply chain under centralized decision-making to maximize overall profit. The optimal supplier emission reduction level e_{SC}^*, manufacturer emission reduction level e_{MC}^* and retail price p_C^* are respectively:

$$e_{SC}^* = \frac{(\gamma+e_0t)[1-(c+te_0)]}{4k-(\gamma+e_0t)^2}; \qquad e_{MC}^* = \frac{\gamma[1-(c+te_0)+(\gamma+e_0t)e_{SC}^*]}{4k-\gamma^2};$$

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$$p_C^* = \frac{1}{2}\left[1 + \left(c + te_0\right) + \gamma\left(e_{SC}^* + e_{MC}^*\right)\right].$$

Proposition 1 Under centralized decision-making without vertical spillover effect, the optimal decisions and profits of the supply chain follow the rules below:

(1) $\frac{\partial e_{SC}^*}{\partial t} > 0$, $\frac{\partial e_{SC}^*}{\partial \gamma} > 0$, $\frac{\partial e_{SC}^*}{\partial k} < 0$; $\frac{\partial e_{MC}^*}{\partial \gamma} > 0$, $\frac{\partial e_{MC}^*}{\partial k} < 0$, $\frac{\partial e_{MC}^*}{\partial t} = 0$;

(2) $\frac{\partial p_C^*}{\partial t} > 0$, $\frac{\partial p_C^*}{\partial \gamma} > 0$, $\frac{\partial p_C^*}{\partial k} > 0$;

(3) $\frac{\partial \pi_{SCC}^*}{\partial t} > 0$, $\frac{\partial \pi_{SCC}^*}{\partial \gamma} > 0$, $\frac{\partial \pi_{SCC}^*}{\partial k} < 0$.

Proposition 1 reveals that a rising EU CBAM carbon tax rate will directly force suppliers to raise their emission reduction levels (manufacturers are not carbon tax payers, so their emission reduction levels are not directly affected by carbon tax), and suppliers cut carbon tax costs by reducing actual carbon emissions; rising consumer low-carbon preference will drive both upstream and downstream to increase emission reduction R&D, which meets the low-carbon demand of the EU market and thus lifts the overall profit of the supply chain; a rising emission reduction cost coefficient will dampen enterprises' enthusiasm for emission reduction, and the supply chain transfers part of the cost pressure to EU consumers by raising product retail prices. The dual incentives of carbon tax and low-carbon preference will significantly boost the overall profit of the supply chain.

3.2. Decentralized decision-making

Under decentralized decision-making, the supplier and the manufacturer conduct a Stackelberg sequential game with the goal of maximizing their own interests: as the supply chain leader, the supplier first decides the independent emission reduction level e_S and the wholesale price w of intermediate products; as the follower, the manufacturer decides its independent emission reduction level e_M and the final product retail price p after observing the supplier's decisions. The supplier's profit function (after deducting production cost, carbon tax cost and its own emission reduction R&D cost) is:

$$\pi_{SD} = \left(w - c\right)Q - t\left(e_0 - e_S\right)Q - \frac{1}{2}ke_S^2 \tag{3}$$

The manufacturer's profit function (after deducting procurement cost and its own emission reduction R&D cost) is:

$$\pi_{MD} = \left(p - w\right)Q - \frac{1}{2}ke_M^2 \tag{4}$$

Substitute the demand function without vertical spillover $Q = 1 - p + \gamma\left(e_S + e_M\right)$ into the above two formulas.

Lemma 2 When vertical spillover effect is not considered, there exists a unique optimal emission reduction level and equilibrium price in the supply chain under decentralized decision-making. The supplier's optimal emission reduction level e_{SD}^*, wholesale price w_D^*, the manufacturer's optimal emission reduction level e_{MD}^* and retail price p_D^* are respectively:

$e_{SD}^* = \frac{(\gamma + e_0 t)[1-(c+te_0)]}{2k-(\gamma+e_0 t)^2}$; $w_D^* = \frac{1}{2}\left[1 + \left(c + te_0\right) + \gamma e_{SD}^*\right]$; $e_{MD}^* = \frac{\gamma\left[1 - w_D^* + \gamma e_{SD}^*\right]}{2k - \gamma^2}$; $p_D^* = \frac{1}{2}\left[1 + w_D^* + \gamma\left(e_{SD}^* + e_{MD}^*\right)\right]$; total supply chain profit $\pi_{SCD}^* = \pi_{SD}^* + \pi_{MD}^*$.

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Proposition 2 Under decentralized decision-making without vertical spillover effect, the optimal decisions and profits of the supply chain follow the rules below:

(1) $\pi_{SD}^{*} > \pi_{MD}^{*}$, meaning the supplier gains higher profit by virtue of its first-mover advantage;

(2) $\frac{\partial e_{SD}^{*}}{\partial t} > 0$, $\frac{\partial e_{MD}^{*}}{\partial t} > 0$, $\frac{\partial w_{D}^{*}}{\partial t} > 0$, $\frac{\partial p_{D}^{*}}{\partial t} > 0$;

(3) $\frac{\partial e_{SD}^{*}}{\partial \gamma} > 0$, $\frac{\partial e_{MD}^{*}}{\partial \gamma} > 0$, $\frac{\partial \pi_{SD}^{*}}{\partial \gamma} > 0$, $\frac{\partial \pi_{MD}^{*}}{\partial \gamma} > 0$; $\frac{\partial e_{SD}^{*}}{\partial k} < 0$, $\frac{\partial e_{MD}^{*}}{\partial k} < 0$, $\frac{\partial \pi_{SD}^{*}}{\partial k} < 0$, $\frac{\partial \pi_{MD}^{*}}{\partial k} < 0$.

Proposition 2 reveals that under decentralized decision-making, a rising EU CBAM carbon tax rate not only forces suppliers to reduce emissions, but also is transmitted to manufacturers through wholesale prices, pushing up product retail prices. To maintain market share, manufacturers indirectly raise their emission reduction levels, realizing indirect sharing of carbon tax costs between upstream and downstream; rising consumer low-carbon preference will promote both upstream and downstream to increase emission reduction R&D. Even with the double marginalization effect, low-carbon preference can still reduce decision-making efficiency loss and lift the profits of all supply chain entities; a rising emission reduction cost coefficient will dampen both parties' enthusiasm for emission reduction, and the cost pressure is passed on layer by layer to EU consumers through price transmission.

Corollary 1 When vertical spillover effect is not considered, $e_{SC}^{*} > e_{SD}^{*}$, $e_{MC}^{*} > e_{MD}^{*}$, $p_{C}^{*} < p_{D}^{*}$, $\pi_{SCC}^{*} > \pi_{SCD}^{*}$.

Corollary 1 indicates that centralized decision-making can effectively eliminate the "double marginalization effect" of decentralized decision-making, drive upstream and downstream of the supply chain to raise emission reduction levels, and at the same time lower product retail prices to enhance EU market competitiveness, so as to maximize the overall profit of the supply chain. The higher the carbon tax rate, the more prominent the emission reduction and economic advantages of centralized decision-making.

4. Emission reduction decisions with vertical spillover effect

Enterprises adopt no or only partial protection measures for emission reduction R&D technologies, resulting in positive vertical spillover effects of upstream and downstream emission reduction technologies in the supply chain ($0 < \eta < 1$). The supplier's effective emission reduction level is $e_S + \eta e_M$, the manufacturer's effective emission reduction level is $e_M + \eta e_S$, the actual carbon emission is $e_0 - (e_S + \eta e_M)$, and carbon tax costs are further reduced with the superposition of both parties' emission reduction results. Following the above research framework, this section analyzes the synergistic impact of carbon tax and vertical spillover under centralized and decentralized decision-making.

4.1. Centralized decision-making

Under centralized decision-making with vertical spillover, the supply chain still takes maximizing overall profit as the goal to jointly decide e_S, e_M and p. Upstream and downstream share emission reduction technology results, cutting overall emission reduction R&D costs and carbon tax costs. The overall supply chain profit function is: $\pi_{SCC\eta} = \left(p - c\right)Q - t\left[e_0 - \left(e_S + \eta e_M\right)\right]Q - \frac{1}{2}ke_S^2 - \frac{1}{2}ke_M^2$. Substitute the demand function with vertical spillover $Q = 1 - p + \gamma(1+\eta)(e_S + e_M)$ into the above formula:

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$$\pi_{SCC\eta} = \left(p - c - te_0 + t\left(e_S + \eta e_M\right)\right)\left[1 - p + \gamma\left(1 + \eta\right)\left(e_S + e_M\right)\right] - \frac{1}{2}ke_S^2 - \frac{1}{2}ke_M^2 \qquad (5)$$

Lemma 3 Under centralized decision-making with vertical spillover effect, there exists a unique optimal emission reduction level and retail price in the supply chain, and $\overset{*}{e}_{SC\eta} = \overset{*}{e}_{MC\eta}$ (symmetric spillover effect + supply chain collaborative decision-making). The optimal emission reduction level and retail price are respectively: $\overset{*}{e}_{SC\eta} = \overset{*}{e}_{MC\eta} = \frac{(1+\eta)(\gamma(1+\eta)+e_0t\eta)[1-(c+te_0)]}{2k-(\gamma(1+\eta)+e_0t\eta)(1+\eta)}$; $\overset{*}{p}_{C\eta} = \frac{1}{2}\left[1 + \left(c + te_0\right) + \gamma\left(1 + \eta\right)^2\left(\overset{*}{e}_{SC\eta} + \overset{*}{e}_{MC\eta}\right)\right]$.

Proposition 3 Under centralized decision-making with vertical spillover effect, the optimal decisions and profits of the supply chain follow the rules below:

$\frac{\partial \overset{*}{e}_{SC\eta}}{\partial \eta} > 0$, $\frac{\partial \overset{*}{e}_{SC\eta}}{\partial t} > 0$, $\frac{\partial \overset{*}{e}_{SC\eta}}{\partial \gamma} > 0$, $\frac{\partial \overset{*}{e}_{SC\eta}}{\partial k} < 0$; $\frac{\partial \overset{*}{p}_{C\eta}}{\partial \eta} < 0$, $\frac{\partial \overset{*}{p}_{C\eta}}{\partial t} > 0$;

$\frac{\partial^2 \overset{*}{e}_{SC\eta}}{\partial t \partial \eta} > 0$, $\frac{\partial^2 \overset{*}{e}_{SC\eta}}{\partial t \partial \gamma} > 0$;

$\frac{\partial \overset{*}{\pi}_{SCC\eta}}{\partial \eta} > 0$, $\frac{\partial \overset{*}{\pi}_{SCC\eta}}{\partial t} > 0$, $\frac{\partial \overset{*}{\pi}_{SCC\eta}}{\partial \gamma} > 0$, $\frac{\partial \overset{*}{\pi}_{SCC\eta}}{\partial k} < 0$.

Proposition 3 reveals that the vertical spillover rate and carbon tax rate form a positive synergistic effect: the higher the spillover rate, the more significant the promotion effect of carbon tax on supply chain emission reduction level; a rising vertical spillover rate can reduce the overall emission reduction cost of the supply chain, drive both upstream and downstream to raise emission reduction levels simultaneously, and at the same time lower product retail prices to further expand EU market demand; rising consumer low-carbon preference will strengthen the synergistic effect of carbon tax and vertical spillover, and the three factors jointly drive a substantial increase in supply chain emission reduction level and overall profit; a rising emission reduction cost coefficient will dampen enthusiasm for emission reduction, and under the vertical spillover effect, the hindering effect of cost increase on emission reduction is further amplified.

4.2. Decentralized decision-making

Under decentralized decision-making with emission reduction vertical spillover, the supplier and the manufacturer make independent decisions with the goal of maximizing their own interests, and the supply chain still follows the Stackelberg sequential game: the supplier first determines the independent emission reduction level e_S and the wholesale price w of intermediate products, and then the manufacturer determines its independent emission reduction level e_M and the final product retail price p. Both parties can share each other's emission reduction technology results to reduce their own R&D costs.

The supplier's profit function is:

$$\pi_{SD\eta} = \left(w - c\right)Q - t\left[e_0 - \left(e_S + \eta e_M\right)\right]Q - \frac{1}{2}ke_S^2 \qquad (6)$$

The manufacturer's profit function is:

$\pi_{MD\eta} = \left(p - w\right)Q - \frac{1}{2}ke_M^2$. Substitute the demand function with vertical spillover $Q = 1 - p + \gamma(1 + \eta)(e_S + e_M)$ into the above two formulas.

Lemma 4 Under decentralized decision-making with emission reduction vertical spillover, there exists a unique optimal emission reduction level and equilibrium price in the supply chain. The supplier's optimal emission reduction level $\overset{*}{e}_{SD\eta}$, wholesale price $\overset{*}{w}_{D\eta}$, the manufacturer's optimal

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emission reduction level $e^*_{MD\eta}$ and retail price $p^*_{D\eta}$ are respectively: $e^*_{SD\eta} = \frac{(\gamma(1+\eta)+e_0 t\eta)[1-(c+te_0)]}{2k-(\gamma(1+\eta)+e_0 t\eta)^2}$; $w^*_{D\eta} = \frac{1}{2}\left[1+\left(c+te_0\right)+\gamma\left(1+\eta\right)e^*_{SD\eta}\right]$; $e^*_{MD\eta} = \frac{\gamma(1+\eta)\left[1-w^*_{D\eta}+\gamma(1+\eta)e^*_{SD\eta}\right]}{2k-\gamma^2(1+\eta)^2}$; $p^*_{D\eta} = \frac{1}{2}\left[1+w^*_{D\eta}+\gamma(1+\eta)\left(e^*_{SD\eta}+e^*_{MD\eta}\right)\right]$; total supply chain profit $\pi^*_{SCD\eta} = \pi^*_{SD\eta} + \pi^*_{MD\eta}$.

Proposition 4 Under decentralized decision-making with vertical spillover effect, the optimal decisions and profits of the supply chain follow the rules below:

$\frac{\partial e^*_{SD\eta}}{\partial \eta} > 0$, $\frac{\partial e^*_{MD\eta}}{\partial \eta} > 0$, $\frac{\partial w^*_{D\eta}}{\partial \eta} > 0$, $\frac{\partial p^*_{D\eta}}{\partial \eta} > 0$; $\frac{\partial e^*_{SD\eta}}{\partial t} > 0$, $\frac{\partial e^*_{MD\eta}}{\partial t} > 0$;

$\frac{\partial \pi^*_{SD\eta}}{\partial \eta} > 0$, $\frac{\partial \pi^*_{MD\eta}}{\partial \eta} > 0$, $\frac{\partial \pi^*_{SD\eta}}{\partial t} > 0$, $\frac{\partial \pi^*_{MD\eta}}{\partial t} > 0$;

$\frac{\partial e^*_{SD\eta}}{\partial k} < 0$, $\frac{\partial e^*_{MD\eta}}{\partial k} < 0$, and $\frac{\partial e^*_{SD\eta}}{\partial k} > \frac{\partial e^*_{SD}}{\partial k}$, $\frac{\partial e^*_{MD\eta}}{\partial k} > \frac{\partial e^*_{MD}}{\partial k}$.

Proposition 4 reveals that under decentralized decision-making, a rising vertical spillover rate can still promote upstream and downstream of the supply chain to raise emission reduction levels and increase profits, and a rising carbon tax rate will also force both parties to reduce emissions, but the double marginalization effect of decentralized decision-making will weaken their synergistic effect; a rising vertical spillover rate will push up both wholesale and retail prices, and suppliers share the benefits of technology spillover by raising wholesale prices; the hindering effect of rising emission reduction cost coefficient on emission reduction is more significant under the vertical spillover effect, and the emission reduction enthusiasm of upstream and downstream in the supply chain is more affected by costs.

Proposition 5 (1) $e^*_{SC\eta} > e^*_{SD\eta}$, $e^*_{MC\eta} > e^*_{MD\eta}$, $\pi^*_{SCC\eta} > \pi^*_{SCD\eta}$;

$e^*_{SC\eta} > e^*_{SC}$, $e^*_{MC\eta} > e^*_{MC}$, $e^*_{SD\eta} > e^*_{SD}$, $e^*_{MD\eta} > e^*_{MD}$;

$\frac{\partial(e^*_{SC\eta}-e^*_{SD\eta})}{\partial \eta} > 0$, $\frac{\partial(e^*_{MC\eta}-e^*_{MD\eta})}{\partial \eta} > 0$, $\frac{\partial(e^*_{SC\eta}-e^*_{SD\eta})}{\partial t} > 0$.

Proposition 5 reveals that whether vertical spillover is considered or not, centralized decision-making outperforms decentralized decision-making in both emission reduction level and overall profit; the higher the vertical spillover rate and carbon tax rate, the wider the emission reduction gap between the two, and the more significant the advantages of centralized decision-making. The vertical spillover effect can significantly lift the emission reduction levels of upstream and downstream in the supply chain: whether under centralized or decentralized decision-making, emission reduction levels with vertical spillover are higher than those without vertical spillover, and the synergistic effect of carbon tax and vertical spillover further widens this gap.

5. Numerical analysis

To intuitively analyze the impacts of EU CBAM carbon tax rate t, emission reduction vertical spillover rate η, consumer low-carbon preference coefficient γ and emission reduction cost coefficient k on supply chain emission reduction level and profit, and verify the correctness of the above propositions and corollaries, this paper sets benchmark parameters with reference to existing studies to meet model constraints: $c = 0.2$, $e_0 = 1$, $t = 0.5$, $\gamma = 0.8$, $\eta = 0.5$, $k = 3$. The single-variable method is adopted to change the values of core parameters and analyze their marginal impacts on supply chain decisions.

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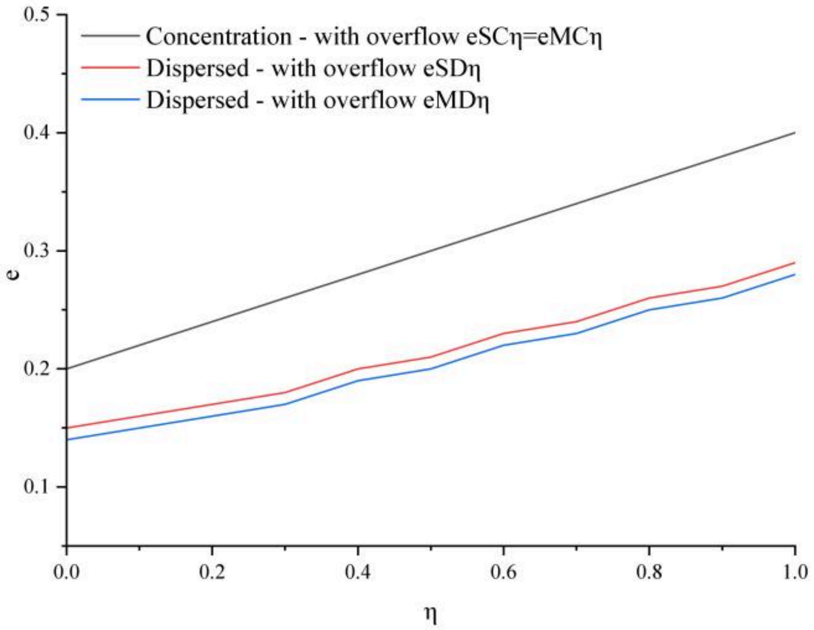

Figure 1. Impact of vertical spillover rate on emission reduction levels of suppliers and manufacturers

Figure 1 shows that the higher the technology sharing ratio, the higher the enterprise emission reduction level, and the promotion effect under centralized decision-making is slightly stronger than that under decentralized decision-making.

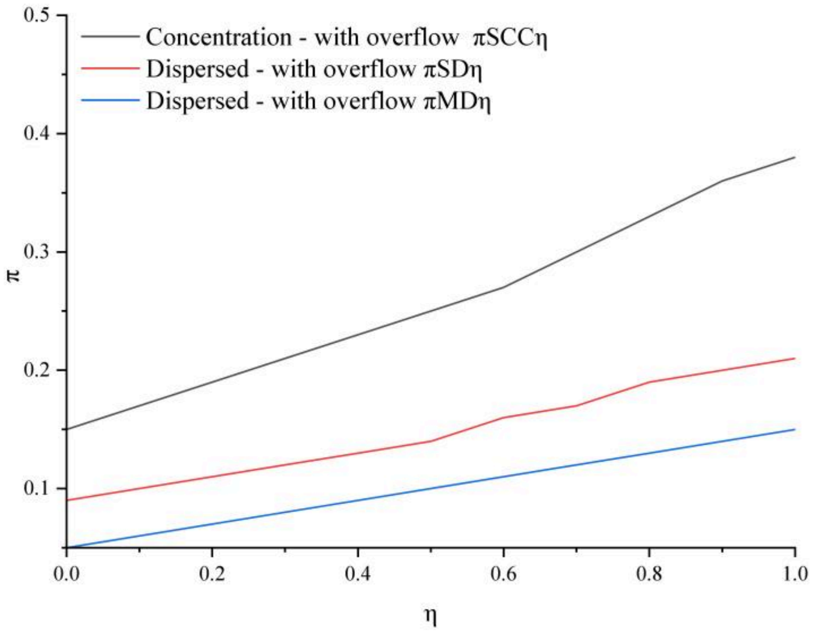

Figure 2. Impact of vertical spillover rate on profits of suppliers, manufacturers and the supply chain

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Figure 2 shows that the higher the vertical spillover rate, the greater the supply chain profit, and the overall profit under centralized decision-making is higher than that under decentralized decision-making.

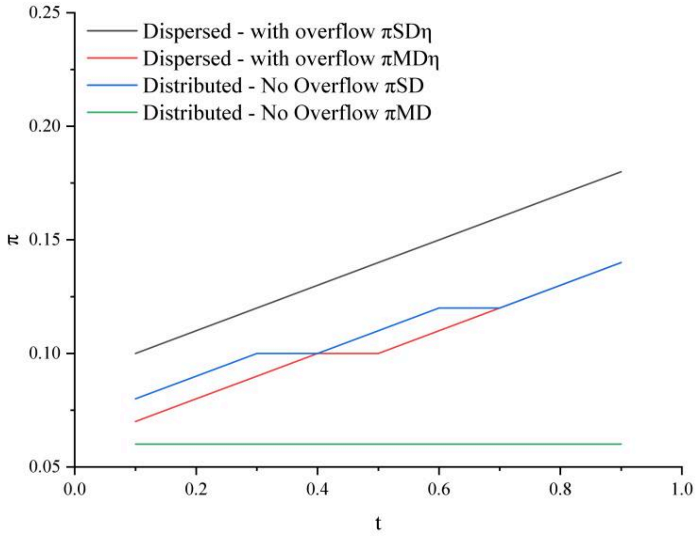

Figure 3. Impact of carbon tax rate on profits of suppliers and manufacturers

Figure 3 shows that the higher the carbon tax rate, the greater the enterprise profit, and the profit gap between the two parties is relatively smaller when vertical spillover exists.

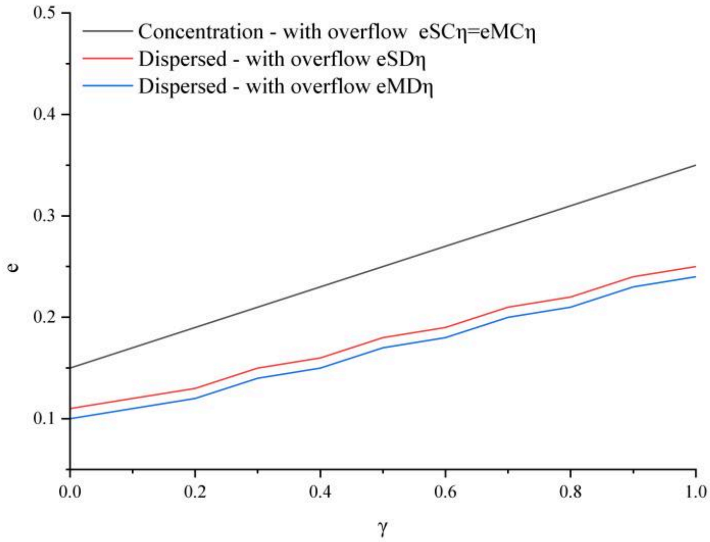

Figure 4. Impact of consumer low-carbon preference and carbon tax rate on emission reduction levels of suppliers and manufacturers

Figure 4 shows that the higher the consumer low-carbon preference and carbon tax rate, the higher the enterprise emission reduction level. The emission reduction level under centralized decision-making is higher than that under decentralized decision-making, and the two factors exert a certain synergistic effect.

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6. Conclusion

The study finds that: (1) EU CBAM carbon tax, emission reduction vertical spillover and consumer low-carbon preference form a positive synergistic incentive, which significantly lifts the supply chain's emission reduction level and the profits of all entities, and the synergistic effect is more prominent under centralized decision-making. (2) A rising emission reduction cost coefficient inhibits supply chain emission reduction, and vertical spillover will aggravate this inhibitory effect; carbon tax can force emission reduction, and under decentralized decision-making, carbon tax costs are indirectly shared by upstream and downstream through wholesale prices. (3) Centralized decision-making always outperforms decentralized decision-making in emission reduction efficiency and overall supply chain profit, and its advantages become more obvious with higher carbon tax and spillover rates; vertical spillover can effectively improve emission reduction and profit levels. (4) Under decentralized decision-making, a rising spillover rate pushes up wholesale and retail prices, and suppliers profit by virtue of their first-mover advantage; under centralized decision-making, a rising spillover rate will lower retail prices and expand EU market demand.

Decision-making implications: (1) For enterprises, upstream and downstream of cross-border supply chains should strengthen emission reduction technology exchange and result sharing, raise the emission reduction vertical spillover rate, and make full use of the synergistic effect of carbon tax and vertical spillover to reduce R&D costs; supply chains should prioritize the centralized decision-making mode, eliminate the double marginalization effect through cost-sharing and profit-sharing contracts, and maximize the triple incentives of carbon tax, vertical spillover and low-carbon preference; as the carbon tax payer, suppliers should take the initiative to increase emission reduction R&D investment, and at the same time share carbon tax costs with manufacturers through reasonable wholesale price setting, while manufacturers should rely on low-carbon preference and technology spillover to raise emission reduction levels to meet EU market demand. (2) The government should strengthen mutual recognition of carbon accounting standards with the EU, promote the alignment of domestic emission reduction technology standards with CBAM, and reduce cross-border trade barriers; launch differentiated supporting policies for cross-border supply chains, grant financial subsidies or tax incentives to enterprises with high spillover rates and high emission reduction levels, and reduce emission reduction and CBAM response costs; step up low-carbon publicity to enhance consumers' low-carbon preference, and at the same time encourage supply chains to build technology sharing platforms to promote the emission reduction vertical spillover effect.

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