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RESEARCH ARTICLE

Impact of Green Credit Incentives on Operational Decisions of Green Supply Chain

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Abstract: Financial incentives have been introduced to guide financial institutions to increase green credit allocation, strengthen environmental risk management, and enhance support for green and low-carbon development. This paper investigated the government's support for the carbon emission supply chain by implementing green credit incentives. Two financial incentives are explored: performance-based incentives and interest subsidies. We conduct game-theoretic models to examine the characteristics and effects of two financial incentives on the supply chain. Our results reveal that: (1) both incentives are effective in scaling up supply chain performance and stimulate investment in emission reduction, while the mechanism differs according to the direct beneficiaries; (2) performance-based incentives are more sensitive to environmental damage, while the optimal subsidy ratio is more sensitive to consumer green awareness, indicating that the bank has an instinctive aversion to the risks inherent in abatement investments; (3) it is optimal for the government to intervene in green credit financing activities when environmental advantages and costs and consumer green consciousness are recognized. Our conclusions suggest the government can determine financial incentives for green credit based on the stage of green transition development and the real, demanding requirements of transition goals.

Keywords: green credit, financial incentives, supply chain management, carbon emission reduction

1. Introduction

Successful green transformation requires the allocation of significant capital investment, which is a major challenge for companies with high levels of risk and limited credit ratings [1, 2]. Green credit finance plays a crucial role in assisting manufacturers in overcoming financial constraints during the green transformation and investment process. The evolution of this phenomenon is currently occurring at a global level [3]. Green credit financing provides financial services support to projects and activities related to sustainable development, with the main objective of incentivizing companies to behave in an environmentally friendly manner [4]. The green finance market refers to a collection of market-oriented strategies and financial tools that possess the capacity to reduce pollutant emissions and protect businesses from unexpected changes in the natural environment [5]. There is a global effort to develop green credit financing incentives. China also implemented a package of green financial subsidies to encourage green manufacturing. The primary targets of prevalent green finance incentives encompass financial organizations, such as banks and financing firms. Within the realm of financial incentives, subsidy policies for green finance can be categorized into two primary groups: interest subsidies targeted toward producers and incentives aimed at banks.

This study focuses on the effects of the two commonly observed green credit subsidy regimes, notably interest subsidies and performance-based incentives. The primary distinction between the two subsidy policies lies in the variation of direct recipients. The interest subsidy program can significantly decrease the financial burden associated with green loans for manufacturers. Manufacturers who satisfy the eligibility requirements for green loans have the opportunity to seek an interest discount under the green interest subsidy program. The implementation of interest subsidies serves to decrease borrowing expenses, so mitigating the risk of debt and consequently lowering the probability of banks experiencing losses related to green lending in the future [6]. For example, the city of Jiangsu subsidizes green bonds issued by non-financial enterprises at a rate of 30% of the annual interest on the bonds [7]. In performance-based incentives, the government gives banks incentives for green credit performance as an instrument to reduce their risk of green credit losses. For example, Xiamen City incentivizes banks by 0.02% of the increase in green credit for the year.

While both policies are frequently applied, a significant body of research in the field of operations management mostly focuses on interest subsidy programs. On the other hand, there has been a scarcity of scholarly research on performance-based incentives that are focused on banks [8, 9]. In addition, a significant portion of research has been dedicated to sectors outside of financing, with subsidies commonly directed toward both consumers and producers. Limited research has been conducted on the impact of green credit incentives specifically aimed at banks and manufacturers about their financing and operational choices. Hence, it is worthwhile to investigate more efficient methods of enhancing the environmental and economic efficiency of the supply chain using green credit incentives. Driven by the existing research void, we have undertaken the task of constructing game-

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theoretic models to address and supplement the current body of literature. Our investigation focuses on the following issues:

(1) How do green credit incentives for different beneficiaries (i.e., the manufacturer and the bank) influence the emission reduction investments and optimal operational decisions of the supply chain?
(2) Is there an optimal stimulus ratio for both financial incentives? If it exists, what factors should policymakers consider while determining that ratio?
(3) Is it possible that one incentive mechanism dominates the other, or do policymakers base their decisions on the orientation of socioeconomic objectives? If the latter, on what criteria does that preference depend?

In order to investigate the aforementioned inquiries, we employ game-theoretic models to analyze the attributes and impacts of two financial incentives on green credit. Our model captures the operational success and social welfare of the supply chain after implementing incentives for either the bank or the business. Moreover, unlike previous research regarding government subsidies in the supply chain [8, 10], we compare the advantages and characteristics of the two subsidy policies. In addition, we identify the significant factors influencing the government's involvement intensity. Furthermore, our research complements the gap regarding the comparison of subsidy policies for green financing. We also compare the cost-effectiveness and social welfare from the government's perspective.

The rest of the paper is organized as follows. In the next section, the review of related literature is presented. Section 3 introduces the assumptions. Section 4 presents the model and derives the equilibrium solutions under both policies and Section 5 compares the equilibrium. In Section 6, we conduct a series of numerical analyses to compare the performance of the supply chain under the two incentive strategies. Section 8 concludes.

2. Literature Review

Our paper falls into two broad areas: green supply chain under government subsidies and the operations–finance interface.

Research in the first stream covers on several themes, including technological investment and innovation [11, 12, 13], low-carbon supply chain management [14, 15, 16, 17], and government incentives [18, 19, 20, 21]. Our paper is more closely related to the literature that studies the impact of policy instruments on abatement investments and green transactions of the supply chain. In this branch, numerous studies focus on the impact of regulations and subsidies on the green supply chain. For example, Cohen et al. [20] demonstrated that the subsidy mechanism coordinates the government and the supply chain without harming the consumers' interests. Yenipazarli [22] illustrates how government regulations affect environmental R&D incentives and emissions costs. Krass et al. [4] show that for eras with substantial environmental damage, a combined carbon tax and subsidy policy has larger social benefits since it boosts pollution costs and decreases investment costs to mitigate them. Hafezi and Zolfagharinia [23] reveal that it is crucial for the government to exercise prudence while implementing regulations, as firms may prioritize bigger profits above maintaining a satisfactory environmental level. Bi et al. [24] reported that there exists a strong correlation between government subsidies and several factors such as the degree of green technology, the coefficient of environmental improvement, and the coefficient of unit cost growth. Therefore, the government can expand the scope of subsidized enterprises when the budget is sufficient.

Also, numerous research examined policy consequences when the subsidy's target varies. Li et al. [25] explored the difference between government subsidies based on levels of emission reduction technology and revealed that the wholesale price is the highest when the government subsidizes the retailer. de la Rue du Can et al. [26] indicate that the impact of financial incentives on efficient technologies effects better. This inspires financial policies for the diffusion of new abatement technologies. Jin et al. [27] investigated the implications of policies that provide loan guarantees to banks and interest subsidies to firms. They also suggested specific conditions for the implementation of these policies, shedding light on concerns with the practice of granting credit subsidies for financing emission reduction efforts. Primarily, there exists a predominance of scholarly investigations about subsidies that are contingent upon operational activities; however, there is a relatively limited body of research concerning subsidies that are contingent for loans and investments in abatement.

Various excellent research in operations–finance interface accumulated mainly related to the following themes, such as operational decisions [28, 29, 30], coordination with contracts [31, 32, 33], and credit risk management [34, 35, 36]. By linking financing to sustainable operations, our study focuses on financing the carbon emission reduction investment. Huang et al. [37] indicate that high-quality green innovation is a plausible mechanism that links green finance with regional green development through enhancing green productivity growth. Dash Wu et al. [38] compared the optimal order quantity for retailers, the optimal wholesale price, and the optimal carbon emission level for manufacturers under bank financing and trade credits and demonstrate that when manufacturers invest in emission reduction, the supply chain can achieve a win-win situation in terms of output and emission reduction. Deng et al. [39] observed that the effect of green credit is considerably larger for manufacturers with higher production costs than those with low production costs. However, when the interest rate of green credit is lower, green suppliers will try to improve the probability of delivery and seek more benefits for all parties in the supply chain, resulting in supply chain performance that is significantly higher than traditional supply chains that do not involve green suppliers. Huang et al. [10] compared green credit with subsidies to investigate the distinction between the two incentive mechanisms and suggested the government provide green credit when the budget is relatively low. Jin et al. [27] explained further the policy effects of providing banks with a green credit guarantee facility, noting that guarantees can help assist with green transition investments by reducing potential losses to banks. Although the aforementioned research has focused on the positive benefits of government subsidies on green financing, it has not yet touched on the differences in the effects of subsidy recipients. Most of the studies take the viewpoint of the manufacturer and the consumers to address the differences in policy effects. In practice, however, subsidizing the manufacturers or the bank generates different impacts on supply chain operational decisions.

Our study complements the existing research in the operations–finance interface in two aspects. On the one hand, we characterize the difference in effect between subsidized the bank and the manufacturer. Our results demonstrate that although both types of subsidies possess good environmental incentive effects, their mechanisms of action differ. Policymakers should also choose subsidy policies according to different circumstances. On the other hand, we investigated the conditions under which the two policies are applicable considering the government's subsidy objective. This is relatively rare in previous studies on green credit subsidies and supply chain management.

3. Model Description

Consider a supply chain consisting of one traditional manufacturer ("he") seeking green transitions with capital constraints and one well-funded retailer ("she") selling products to consumers with green preferences. The bank provides green credit financing to the manufacturer with transition capital constraints under financial incentives. The manufacturer's product cost is denoted as c, whereas the wholesale price provided to the retailer is represented as w_i. The consumers buy the products at the retail price p. We assume the retail price p is captured by an inverse demand function $p(q) = a - q_i + \gamma e$ [40], where a represents the market size and γ is the consumers' green awareness.

We use the parameter $e_i(i = P, S)$ to represent the manufacturer's carbon emission level per unit product after emission reduction. Such as Bian et al. [41] and Fan et al. [40], the abatement cost is denoted as $\frac{1}{2}ke_i^2$. Based on the statistical data provided by the People's Bank of China, approximately 68% of green loans are allocated specifically toward initiatives aimed at enhancing emission reduction efficiency. Therefore, the manufacturer endeavors to secure the green loan from a financial institution, leveraging the support of the green credit incentive policy. Assuming the interest rate of the green loan is r_i and the requested loan amount is $\frac{1}{2}ke_i^2(1 + r_i)$. Without loss of generality, assume the manufacturer's funds available for abatement are zero.

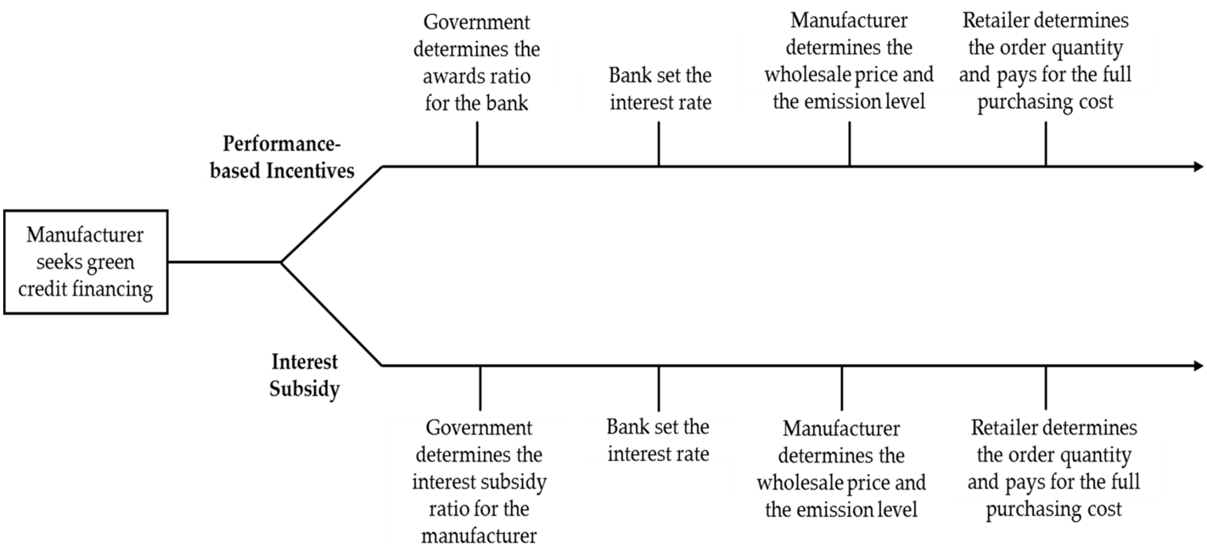
There are two types of incentives to encourage the manufacturer to invest in emission reduction, which are performance-based incentives and interest subsidies. Consistent with financial practice, performance-based incentives policy rewards the bank that employs green credits, whereas interest subsidy provides the manufacturer a certain ratio of green loan interest. The difference between subsidy policies is that governments subsidize different targets and costs. The government chose instead to provide interest subsidy at a ratio θ to the manufacturer or subsidies at ratio δ to the bank. Other relevant parameters are listed in Table 1.

Table 1
Notations

Notation	Description
w_i	Unit wholesale price of the product
e_i	Unit carbon emission level of the product
q_i	Order quantity
r_i	The interest rate of green credit
p	Unit price of the product
a	Total market
c	Unit cost of the manufacturer's product
k	Cost factor related to the unit carbon emission level
γ	Consumers' green awareness
δ	Awards ratio under performance-based incentives, $0 < \delta < 1$
θ	Subsidy ratio under interest subsidy policy, $0 < \theta < 1$
π_i^M	Manufacturer's profit
π_i^R	Retailer's profit
π_i^B	Bank's profit
C_i	Cost of government under each policy
b	Environmental damage to unit product

The supply chain adheres to the Stackelberg game framework, wherein the decision-making process unfolds in the following manner. As shown in Figure 1, first, the bank takes the initial step by announcing the interest rate of the green loan. Second, the manufacturer decides the wholesale price and the abatement level after considering financing costs, and finally, the retailer determines the order quantity. Other assumptions involved in our model are the following: Assume all the players are risk neutral, and all parameters are common knowledge [42]. Similar to the literature, we do not consider the bankruptcy scenario [43, 44, 45]. In addition, we use subscripts "P" and "S" to differentiate between both incentive policies, where "P" represents performance-based incentives

Figure 1
The sequence of events under two incentive policies



policy and "S" represents interest subsidy. Moreover, let the subscripts "N" denote the scenario in which the government does not offer any incentives.

4. Equilibrium Analysis of Two Incentive Policies

In this section, we conduct two models to analyze the effects of the two policies. The optimal solutions of each member are investigated, as well as the policy effects and implications.

4.1. Performance-based incentives

Under the performance-based incentives policy, the government provides awards to the bank to encourage green lending. The total amount of the green loan issued by the bank to the manufacturer is $\frac{1}{2}ke_P^2$ at rate r_P. Accordingly, the government grants the bank a percent awards at ratio δ in line with the green credit offer. Therefore, the bank reaps the interest and awards equally

$$\pi_P^B = \frac{1}{2}ke_P^2(r_P + \delta) \tag{1}$$

And total cost of the subsidy as indicated by the government is

$$C_P = \frac{1}{2}ke_P^2\delta \tag{2}$$

The emission reduction investments convert to fixed costs for the manufacturer, to which he adds generation costs *to* determine the wholesale price. Afterward, the retailer accepts the wholesale price and decides on the order quantity depending on the consumer preference. The profits of the manufacturer and the retailer are described as follows.

$$\pi_P^M = \left(w_p - c\right)q_p - \frac{1}{2}ke_P^2(1 + r_P) \tag{3}$$

$$\pi_P^R = \left(a - q_p + \gamma e_P\right)q_p - w_p q_p \tag{4}$$

Solve this Stackelberg game by reverse deduction. Determine the optimal order quantity for the retailer from Equation (4) and substitute it to Equation (3). Then substitute the solutions of w_p and e_p into Equation (1). The following conclusion can be concluded.

Proposition 1: For any given δ under performance-based incentives, the optimal operational decisions of the supply chain members are given in Table 2.

Table 2
Optimal operational decisions under performance-based incentives

q_P^*	$\frac{(a-c)(8k(1-\delta)-\gamma^2)}{8(4k(1-\delta)-\gamma^2)}$
w_P^*	$\frac{1}{2}(a+c)\left(1+\frac{\gamma^2}{2(4k(1-\delta)-\gamma^2)}\right)$
e_P^*	$\frac{(a-c)\gamma}{2(4k(1-\delta)-\gamma^2)}$
r_P^*	$\frac{4k-\gamma^2-8k\delta}{4k}$
π_P^R*	$\left(\frac{(a-c)(8k(1-\delta)-\gamma^2)}{8(4k(1-\delta)-\gamma^2)}\right)^2$
π_P^M*	$\frac{(a-c)^2(8k(1-\delta)-\gamma^2)(4k(1-\delta)-3\gamma^2)}{32(4k(1-\delta)-\gamma^2)^2}$
C_P*	$\frac{(a-c)^2k\gamma^2\delta}{8(4k(1-\delta)-\gamma^2)^2}$

Proposition 1 reports that the optimal decisions of the players are driven by two key parameters: the consumers' green awareness γ and the cost factor of emission investments k. When the consumers' green awareness increases, the manufacturer is motivated to reduce emissions since the market demand provides a commitment to recovering abatement costs. As γ increases, the products sell better and the supply chain has a more robust of recovering profits. As a result, the interest rate of the green loan decreases accordingly. On the contrary, with the increase in the cost of the carbon emission investment k, the optimal emission reduction level e_P^* is strongly curbed, which leads the manufacturer to raise the optimal wholesale price w_P^* to balance profits with costs. This further resulted in lower order quantities of the retailer, which enlightens that the key to encouraging the manufacturer's emission reduction level is to reduce the financing costs of abatements.

Additionally, it reports that the production costs and market size significantly affect the profits of supply chain members but not the green loan interest. The reason behind this is that the bank places greater emphasis on customers' preferences rather than market size in order to secure repayment of the green loan. This is because the loan is utilized by the manufacturer to mitigate emissions, which will ultimately be passed on to consumers. And there is a substantial relationship between the size of the market and the financial profit of the supply chain members. Conversely, the higher the production costs of the manufacturer, the less the profits. This is because $4k - \gamma^2$ represents the difference between abatement costs and consumers' green awareness. When this difference is smaller, the level of optimal decision making of supply chain members is higher. The performance-based awards of δ stimulate the manufacturer to invest in emission reduction by reducing this gap. This indicates that performance-based incentives policy effects.

We can obtain the following corollary according to the above calculation results.

Corollary 1: $\frac{dq_P^*}{d\delta} > 0$, $\frac{dw_P^*}{d\delta} > 0$, $\frac{de_P^*}{d\delta} > 0$, $\frac{d\pi_P^S}{d\delta} > 0$, $\frac{d\pi_P^{M*}}{d\delta} > 0$, $\frac{dr_P^*}{d\delta} < 0$.

As shown in Corollary 1, the ratio δ of performance-based incentives exhibits a significant positive impact on the operational decisions of the supply chain members. It can be observed that r_P^* decreases with δ increases, while other parameters increase with it. As the financing costs decrease, the market competitiveness of manufacturers' wholesale prices increases, and the retailer's order volume grows. As a result, the manufacturer's profits increase as w_P^* increases and retailer's profits increase as q_P^* increases. This means the performance-based incentives policy benefits the supply chain members and the consumers despite the direct beneficiary is the bank. That is to say, δ lowers the financing costs by providing the bank risk-compensations, which in turn allows the green loan at a lower interest rate. As indicated previously, the fundamental reason is that it helps the manufacturer to lower his abatement costs. It should be noticed that the direct beneficiary of performance-based incentives is the bank. The mechanism of its action is to drive down the price of financial services by increasing the profits of granting green loans.

4.2. Green credit interest subsidy

In this section, we consider the scenario that the government provides interest subsidy to alleviate the manufacturer's financing constraints. Under green credit interest subsidy policy, the government helps the manufacturer reduce financing costs by providing interest subsidies. Considering the green credit rate set by the bank is r_S, and the total amount of interest charged by the bank is $\frac{1}{2}ke_S^2r_S$. Thus, the interest income earned by the bank through green credit is

$$\pi_S^B = \frac{1}{2}ke_S^2r_S \tag{5}$$

The interest subsidy rate provided by the government is θ. Then, the cost to the government to incentivize the manufacturer to invest in emissions reductions is

$$C_S = \frac{1}{2} k e_S^2 \theta \quad (6)$$

Afterwards, the manufacturer decides the level of carbon abatement investments and wholesale price based on the level of interest rate r_S and the government subsidy θ. After receiving the interest subsidy from the government, the manufacturer operates production and sells the products to the retailer at w_S. The profits of the manufacturer and the retailer are

$$\pi_S^R = (a - q_S + \gamma e_S) q_S - w_S q_S \quad (7)$$

$$\pi_S^M = (w_S - c) q_S - \frac{1}{2} k e_S^2 (1 + r_S - \theta) \quad (8)$$

Solving above problem by using converse-solving method similar to Proposition 1, we can summarize each member's equilibrium strategy as follows.

Proposition 2: Under interest subsidy, the optimal operational decisions of the supply chain members are given in Table 3.

Table 3
Optimal operational decisions under interest subsidy

q_S^*	$\frac{(a-c)(8k(1-\theta)-\gamma^2)}{8(4k(1-\theta)-\gamma^2)}$
w_S^*	$\frac{1}{4}\left(2(a+c) + \frac{(a-c)\gamma^2}{4k(1-\theta)-\gamma^2}\right)$
e_S^*	$\frac{(a-c)\gamma}{2(4k(1-\theta)-\gamma^2)}$
r_S^*	$\frac{4k(1-\theta)-\gamma^2}{4k}$
π_S^R*	$\frac{(a-c)^2(8k(1-\theta)-\gamma^2)^2}{64(8k(1-\theta)-\gamma^2)^2}$
π_S^M*	$\frac{(a-c)^2(8k(1-\theta)-\gamma^2)}{16(4k(1-\theta)-\gamma^2)}$
$C_S{}^*$	$\frac{(a-c)^2 k\gamma^2\theta}{8(4k(1-\theta)-\gamma^2)^2}$

By observing Proposition 2, we can conclude that the characteristics of the optimal solutions are similar to the previous scenario. Likewise, the manufacturer and the retailer's profits grow as market size expands and drop as costs increase. At the same time, the gap between the cost factor of carbon emission k and the consumers' green awareness γ still be the important factors to be considered. Where k leads to a tendency for players to be conservative in their operational decisions, while γ reinforcing the positive characteristics of their decisions preferences. Similarly, the government's interest subsidy policy led to lower costs for the manufacturer through offering interest subsidies to balance the financial liabilities of emission reduction costs. We can observe that $4k(1-\theta) - \gamma^2$ shrinks as θ increases. Consequently, the bank still weighs abatement costs and consumers' preferences when determining the interest rates, unaffected by market size and intrinsic expenses of the manufacturer, while the manufacturer and the retailer will constantly balance the impact on financial performance of market size, product costs, carbon emission investments, and profits.

We can conclude that the characteristics of each parties' equilibrium decisions are shown in Corollary 2.

Corollary 2: $\frac{dq_S^*}{d\theta} > 0$, $\frac{dw_S^*}{d\theta} > 0$, $\frac{de_S^*}{d\theta} > 0$, $\frac{d\pi_S^{S*}}{d\theta} > 0$, $\frac{d\pi_S^{M*}}{d\theta} > 0$, $\frac{dr_S^*}{d\theta} < 0$.

The above corollary suggests that under interest subsidy policy, the interest rate r_S^* decreases in θ while the other decision parameters increase in θ, including the optimal order quantity q_S^*, the optimal wholesale price w_S^*, and the carbon emission level e_S^*. The higher the subsidies, the greater the incentive for manufacturers to reduce emissions, resulting in better selling products as a result of high consumer preferences for low-carbon products. As a result, the financial performance of the manufacturer and the retailer increases with higher subsidies. The mechanism of action reduces the abatement financing costs of the manufacturer, sending positive signals to the supply chain.

The difference is that the manufacturer is the direct recipient of the interest subsidy. And its mechanics of policy implementation are designed to enhance the incentive to reduce emissions by directly reducing the manufacturer's investment costs of reducing emissions. With the increase in the subsidy intensity, the manufacturer benefits from carbon emission investments and the increased value of production, while the retailer benefits from the increased consumers' green awareness.

5. Comparative Analysis between Two Polices

In this section, we further compare the effects and the social welfare of the two green credit incentive policies based on the optimal operational decisions of the supply chain in the above section. For ease of analysis, we use the no-subsidy scenario as a benchmark. We use the subscript "N" to represent this unsubsidized scenario and the optimal operational decisions are equivalent to $\delta = \theta = 0$.

5.1. Comparison of optimal decisions

First, we analyze the effects of the two subsidy policies by comparing the optimal operational decisions and profits of each member. Accordingly, we can obtain Proposition 3 and Proposition 4. Next, we analyze the changing characteristics of financing risks and costs with policy support by comparing green credit rates in Proposition 5.

Proposition 3: The equilibrium strategies associated with the decision variables possess the following properties: $q_P^* > q_S^* > q_N^*, w_P^* > w_S^* > w_N^*, e_P^* > e_S^* > e_N^*$ if $\delta > \theta$.

Proposition 3 is intuitive. By comparing the optimal decisions of both players, it can be seen that if the support ratio δ is higher than θ, the optimal decisions will be better according to the corresponding policy, and vice versa. Moreover, both policies effect better than the no-subsidy scenario. Due to the fact that the effects of the two policies are strikingly comparable, it is evident that both policies alleviate the financial constraints as well as the abatement costs of the manufacturer.

The important difference between the two policies is that the direct beneficiaries are different. Under interest subsidy policy, the manufacturer is the direct beneficiary. Due to the high risk associated with abatement investments, however, the bank may be less motivated to issue the green loan under interest subsidy policy. Thus, it suggests that target the bank as the directly beneficiary under performance-based incentives effetely motivates the bank to provide financial support to the manufacturer [46]. However, the negative consequence of this policy is that the bank does not necessarily reduce the financing interest rates as a result of the performance awards. Thus, the reduction of the manufacturer's financing costs is also subject to financial market competition. This suggests that raising incentives for the bank to provide green loans is just as crucial as lowering the cost of emission reductions to motivate the manufacturer to make the green transition.

This suggests that policymakers consider the direct beneficiaries and negative effect during the policy implementation when deciding on the manner and intensity of subsidies.

Based on Proposition 3, we can conclude the following proposition.

Proposition 4: Compare the profits of both players,
(1) if $\delta > \theta$, then $\pi_P^{S^*} > \pi_S^{S^*} > \pi_N^*$, $\pi_P^{M^*} > \pi_S^{M^*} > \pi_N^*$;
(2) if $\theta > \delta$, then $\pi_S^{S^*} > \pi_P^{S^*} > \pi_N^*$, $\pi_S^{M^*} > \pi_P^{M^*} > \pi_N^*$.

Proposition 4 illustrates that the subsidy ratio affects the profits of supply chain members by influencing their optimal operational decisions. If $\delta > \theta$, the manufacturer and the retailer perform better, and vice versa. It appears that both parties' profits are highly sensitive to the level of support ratio δ and θ), especially when the beneficiary is not the manufacturer. Regardless of whether they are direct beneficiaries or not, that manufacturer and retailer will always prefer policies with higher subsidized rates. This is because both green financing incentives are effective at mitigating the cost of investment in abatement.

Combined with Proposition 3, it suggests that the policymakers select appropriate subsidy policy with comparable effects and direct beneficiaries. More specifically, when the bank is hesitant to lend due to green loan risks, the government can stimulate the expansion of green credit business by providing performance-based incentives. In contrast, interest subsidies policy effects when the green financing is booming in banking sector while the manufacturer is reluctant to invest or trapped in financial difficulties. In general, the performance-based incentives are more appropriate for the early stage of green credit, i.e., when the granting scale of green loans is still nascent. In comparison, the interest subsidy policy is better adapted for the supply chain transformation phase, particularly in traditional areas with greater capital limitations and heavier assets. This is consistent with Lee & Lee [47]. It is important to note that the awards for the bank do not necessarily help diversify the risk of the green loan, especially for manufacturers with high financial burdens, where access to the green loan and financial ability to repay are of equal importance.

Next, we compare the bank's interest incomes of green credit and the government's expenditure on the two financial incentives to further conclude the policy mechanism.

Proposition 5:
(1) when $\delta > \frac{\theta}{2}$, $r_P^* < r_S^*$, otherwise $r_S^* < r_P^*$;
(2) the government's expenditure is highly depending on the support ratio, where $\delta > \theta$, then $C_P^{G^*} > C_I^{G^*}$, and if $\theta > \delta$, then $C_I^{G^*} > C_P^{G^*}$.

Proposition 5 characterizes that the performance-based incentives are more effective than interest subsidies at reducing green credit interest, as the bank is much more motivated by the awards. It suggests that the awards act as a green credit risk premium. Otherwise, the bank demands relatively higher interest compensation under the interest subsidy policy.

The cost of government subsidies, on the other hand, remains the same as in the previous scenario and is primarily determined by the subsidy ratio δ and θ. When δ is higher than θ, then performance-based incentives are less costly and the supply chain prefers this over interest subsidy. Conversely, if δ is greater than θ, then interest subsidy policy is much economic. It also suggests that policy objectives are proportional to expenditure costs, regardless of the government's policy choices. The greater the government's desired short-term policy effect, the greater its subsidy expenditures will be. Consequently, it is crucial to provide subsidies while investigating long-term mechanisms to promote low-carbon investments.

5.2. Comparative analysis of social welfare

In the policy development process, the government seeks to maximize social welfare with less incentive costs. According to Krass et al. [4], social welfare can be expressed as:

$$\text{Social welfare} = \text{Manufacturer's profit} + \text{Retail's profit} + \text{Consumer surplus} - \text{Government's total subsidy} - \text{Environmental Impact}.$$

Consumer surplus is the area between a demand curve and a given price that is used to calculate consumer satisfaction [20]. We denote the consumer surplus as:

$$\text{Consumer surplus} = \frac{1}{2} {q_i^*}^2$$

Considering the environmental impact per unit of product is b, the total environmental impact of the supply chain is

$$\text{Environmental Impact} = b{e_i}^*{q_i}^*$$

Therefore, the corresponding incentive costs and consumer surplus can be determined, as well as the environmental impact. The social welfare can be calculated as follows.

$$SW_P = \frac{(a-c)^2(448k^2(1-\theta)^2+\gamma^3(8b+11\gamma)-16k\gamma(4b(1-\theta)+\gamma(9-8\theta)))}{128(4k(1-\theta)-\gamma^2)^2}$$

$$SW_S = \frac{(a-c)^2(448k^2(1-\theta)^2+\gamma^3(8b+11\gamma)-16k\gamma(4b(1-\theta)+\gamma(9-8\theta)))}{128(4k(1-\delta)-\gamma^2)^2}$$

The social welfare illustrates that the impact of the key factors is much magnified. Under the two policies, $(a-c)^2$ implies that social welfare is rooted in market size and the constant cost of manufacturing. We can also observe that the impact of consumers' green awareness γ on social welfare is also enhanced. Thus, the government can increase social welfare by developing a subsidy redemption procedure linked to green consumer behavior.

5.3. Optimal support ratio under each policy

Regarding social welfare, it is difficult to determine whether incentive policy is superior. However, the ideal amount of government subsidies can be determined by maximizing social welfare goals. Hence, a natural question arises: what is the rate of subsidy that maximizes social welfare? How should the government choose its subsidy strategy? Therefore, we further analyze subsidy rates with the objective of maximizing social welfare. The optimal support ratio of the two policies is summarized as follows.

$$\delta^* = \frac{16k(2b-\gamma)+5\gamma^3}{32k(b-\gamma)}$$

$$\theta^* = \frac{32k(b-\gamma)+5\gamma^3}{16k(2b-3\gamma)}$$

According to the optimal support rate, it can be summarized that it is influenced by three main factors: the cost of abatement investment k, consumers' green awareness γ, and, most importantly, the environmental damage b. In particular, the impact of abatement investment costs on the optimal level of interest subsidies is more moderate than that of performance-based incentives (i.e., $\frac{d\theta^*}{dk} < \frac{d\delta^*}{dk}$)). This is because interest subsidy is more effective in reducing the cost of abatement investments of the manufacturer, as demonstrated in the previous section. Therefore, the interest subsidy policy is more appropriate if the primary objective is to reduce the emission reduction costs.

The variation of δ^* and θ^* with γ is intuitive. The correlation indicates that if $b > \gamma$, then $\frac{d\delta^*}{d\gamma} > 0$ and $\frac{d\theta^*}{d\gamma} > 0$ exits, and if $b < \gamma$, the direction of the first-order derivative will be diametrically opposite. This demonstrates that when the environmental impact of the product is severe, the consumers' green awareness γ increases with the intensity of the subsidy. This is due to the more visible environmental improvements produced by the subsidy. However, when the environmental impact is tiny or when consumers have a high level of environmental awareness, the impact of subsidies on γ is negligible, and the marginal social welfare feedback is insignificant. This characteristic suggests policymakers concentrate subsidies on areas with high environmental impacts while simultaneously promoting eco-friendly awareness among consumers.

Furthermore, it reveals that the optimal decision decreases in b. The higher the environmental damage, the lower the government's incentive to subsidize it. This is because environmental damage reduces social welfare. In addition, some heavy manufacturing industries with large and obsolete assets face greater barriers to financing the green transition. The bank is more likely to refuse to lend to such high-risk, low-return projects because of the meager cost compensation provided by interest subsidies. Therefore, the government should take into account consumers' green awareness and environmental damage when formulating subsidy strategies.

Based on the above analysis of the factors affecting the support rate, we analytically obtain Proposition 6.

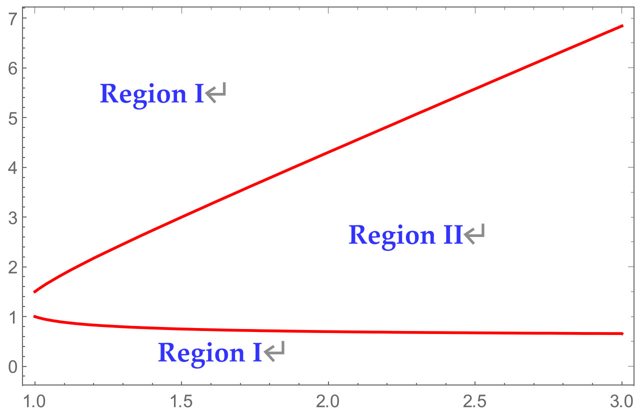
Proposition 6:

(1) The subsidy ratio $\delta^* > \theta^*$ holds when $\gamma > \frac{24}{25}$ and $b \in \left[\frac{5\gamma}{4} - \frac{1}{4}\sqrt{-24\gamma + 25\gamma^2}, \frac{5\gamma}{4} + \frac{1}{4}\sqrt{-24\gamma + 25\gamma^2}\right]$, and the government should implement performance-based incentives policy;

(2) Otherwise, $\delta^* \leq \theta^*$ when $b \in \left(-\infty, \frac{5\gamma}{4} - \frac{1}{4}\sqrt{-24\gamma + 25\gamma^2}\right] \cup \left[\frac{5\gamma}{4} + \frac{1}{4}\sqrt{-24\gamma + 25\gamma^2}, +\infty\right)$, the interest subsidy policy is more appropriate.

Proposition 6 can be derived from the difference between δ^* and θ^*. We use to clearly express the conclusion. The area in the middle of the two functions (Region II) in Figure 2 represents the performance-based incentives area, while the other two areas (Region I) represent the interest subsidy policy. As a whole, performance-based incentives policy is more effective in stimulating green investments for heavy polluters. Specifically, when consumers' green awareness is low or extremely high, the government can choose the interest subsidy policy as it results in relatively higher social welfare. To maximize social welfare, the government may select performance-based incentives when the level of environmental consciousness among consumers is in the middle range. While selecting an acceptable subsidy policy, the government can also design a consumer awareness stimulation program to complement the subsidy strategy to achieve the administrative goal of maximizing social welfare.

Figure 2
Impact of b and γ on the government's policy choice



6. Numerical Simulations

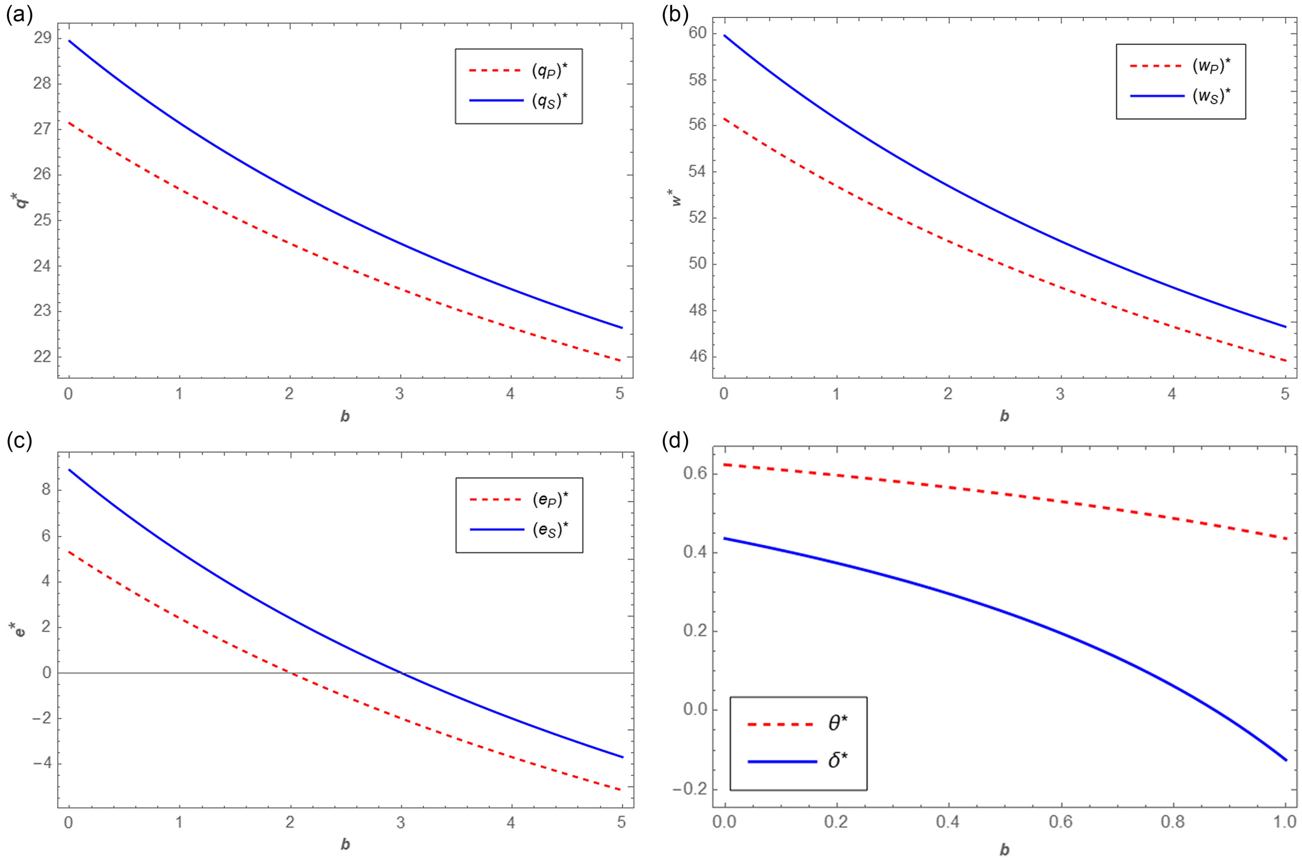
In this section, we conduct numerical experiments to check the robustness of the above analytical insights. We investigate the impact of the green financing incentive policies on the operational decisions and profits of the supply chain. We first examine the impact of the environmental damage b on the profits and the government's return on subsidy expenditure, followed by the impact of the consumers' green awareness. The relevant parameters are set as follows: $a = 100,\ c = 2, k = 10, \gamma = 2, b = 1.5$.

6.1. Effect of environmental damage

Figure 3 depicts the impact of environmental damage on the optimal operational decisions and the optimal subsidy ratio. As analyzed in the preceding section, Figure 3 illustrates that as the environmental damage b increases, the optimal operational decisions of the supply chain and the optimal subsidy ratio reduce. Especially when b is rather significant, the optimal emission reduction level will be overloaded and turn negative. According to Figure 3(a) and (b), it can be observed that environmentally damaging products are not performing well on the market, nor do they have a clear price advantage. This explains why backward production capacity is frequently confronted with more difficult green transformation challenges. This suggests the government to provide necessary financial incentives for such situations. Figure 3(c) demonstrates that the optimal emission reduction level reduces as environmental damage increases, particularly when environmental damage is severe and investment in emission reduction is not cost-effective. Combined with Figure 3(d), the government tends to employ interest subsidies in regions where environmental harm is severe. In situations with minimal environmental damage, the optimal subsidy ratio is frequently greater in situations with substantial environmental impacts. Moreover, as discussed in the preceding section, the interest subsidy policy is less sensitive to environmental damage. This is because green loans in regions with greater environmental damage tend to be riskier, and banks are less interested due to risk control concerns.

Next, we consider the effect of b on supply chain performance and policy effectiveness. Figure 4(a) demonstrates that even with subsidies, the retailer's profits are vulnerable to environmental damage due to consumers' green preferences. The greater the b, the meager the profits. Although retailers will indirectly benefit from providing upstream subsidies, the adopted policy has little impact on the magnitude of their returns, as their profit trends are very similar in both scenarios. However, the manufacturer's profits show significant differences between the two policies. This characteristic can be observed in Figure 4(b), where the interest subsidy dramatically impacts the manufacturer's profits, especially when the environmental impact is small. Under the performance-based incentives, however, the manufacturer' profits are more stable. Nonetheless, as environmental damage continues to increase, the manufacturer's profits under the two policies intersect, inverting the relationship between the comparative results of profits. Figure 4(c) reveals that environmental damage significantly limits the impetus for support expenditures, and the greater the damage, the lower the expenditures. It also reports that this diminishing power is diminishing, i.e., the

Figure 3
Impact of b on the (a) optimal order quantities, (b) emission reduction level, (c) wholesale price, and (d) optimal subsidy ratio



government always tends to subsidize areas where environmental damage is relatively low and improvement is obvious, whereas it is extremely reluctant to subsidize regions where environmental damage is high and the subsidy is not obvious. Finally, Figure 4(d) reveals the relationship between social welfare and b. It shows that the social welfare exhibits a smile curve with environmental damage.

In general, b reflects the environmental value derived from emission reduction level. It reflects that the government incentives are always more efficient for products with higher environmental value after abatement. Given the environmental damage, the government can select the appropriate ratio of subsidy to maximize the efficiency of budget expenditures. Therefore, it is required to analyze the environmental harm to assess its extent before deciding the subsidy policy.

6.2. Effects of consumers' green awareness

Figure 5 illustrates the impacts of consumers' green awareness γ on the supply chain and the both policies. From Figure 5(a) and (b), it reflects that the trend of optimal order quantities and wholesale price is extremely comparable. The higher the γ, the more evident the benefits of the two variables. When γ is low, the change of the two variables is not readily apparent. However, when γ rises, the growth rate of the two variables accelerates substantially. Figure 5(c) reveals that when γ is very low and close to zero, the emission reduction level of the manufacturer is very weak or even negative. Whereas when γ is strong, i.e., the market's green consumption is maturity, the manufacturer emission reduction level also raises to serve the market. Similarly, when γ is strong, both the optimal subsidy ratio increases as well in Figure 5(d). This is because the marginal returns to social welfare from government subsidies are substantial when the market is encouraged to purchase green products. The government is more willing to provide subsidies to regions where the market is more environmentally conscious. This again suggests the policymakers to pay equal attention to the sensitization of consumers when design the subsidies policy.

As seen in Figure 6, γ influences the strength of the manufacturer and retailer's profits as well as the government's decision. First, γ positively influences the profits of both parties, although the intensity of the influence varies. Figure 6(a) as the retailer interacts directly with consumers, its profits rise significantly with γ, under both policies. Second, Figure 6(b) shows that the manufacturer's profit is tempered by γ, particularly while γ is weak. And the variance in manufacturer's profit under the interest subsidy is not substantial until strong green sensitivity arises, at which point the manufacturer's profit increases dramatically. When the immediate beneficiary of the performance-based incentives is the bank, the manufacturer will also gain, although to a lesser extent than the interest subsidy, as analyzed in the previous section. At last, as γ rises, not only will the government budget spend less on subsidized measures, but there will also be an increase in social welfare, as shown in Figure 6(c) and (d). In conclusion, when the beneficial benefits of γ combined subsidy schemes are substantial, the government policy

Figure 4
Impact of b on (a) retailer's profit, (b) manufacturer's profit, (c) expenditures for corresponding policies, and (d) social welfare

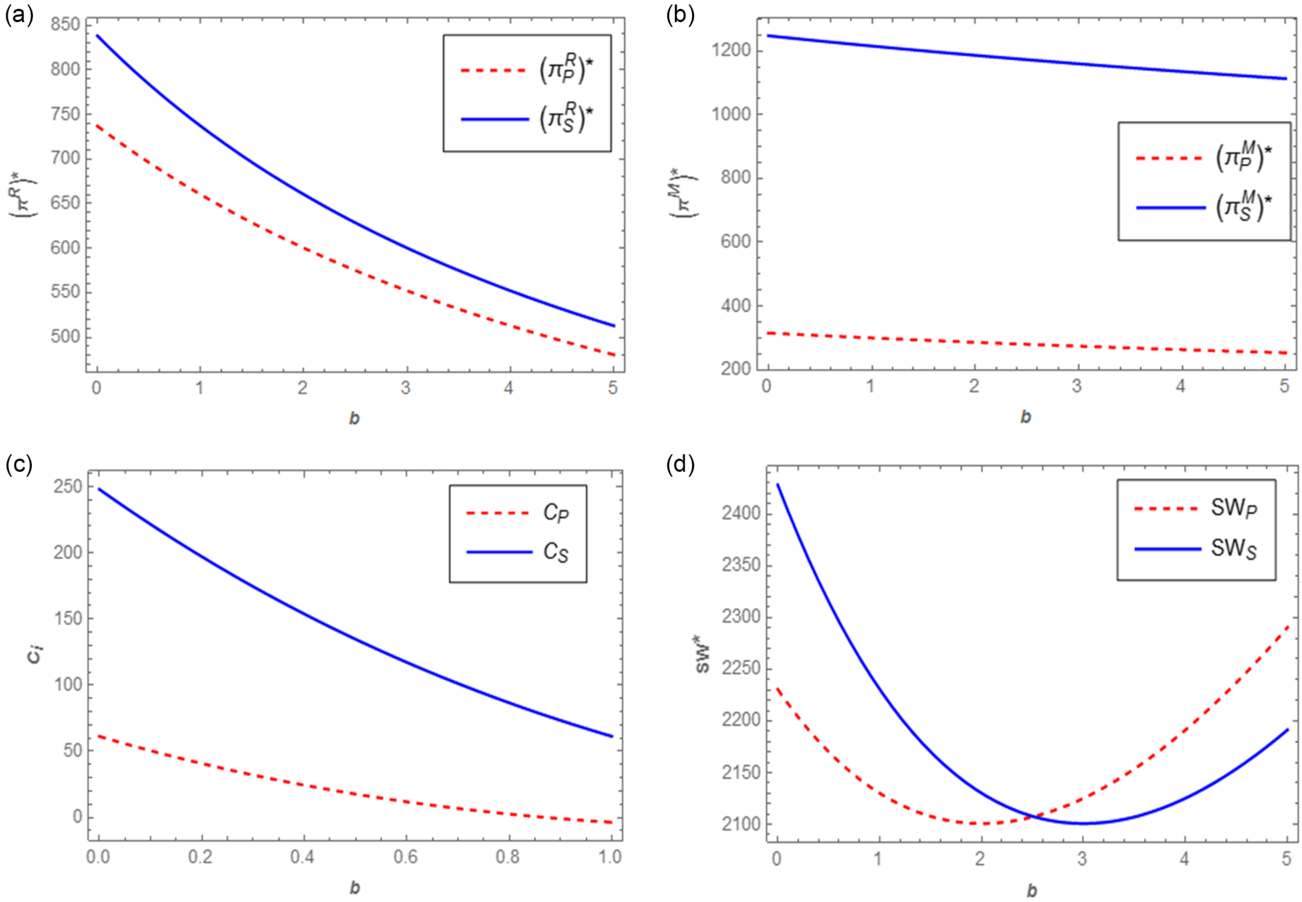


Figure 5
Impact of γ on the (a) optimal order quantities, (b) wholesale price, (c) emission reduction level, and (d) optimal subsidy ratio

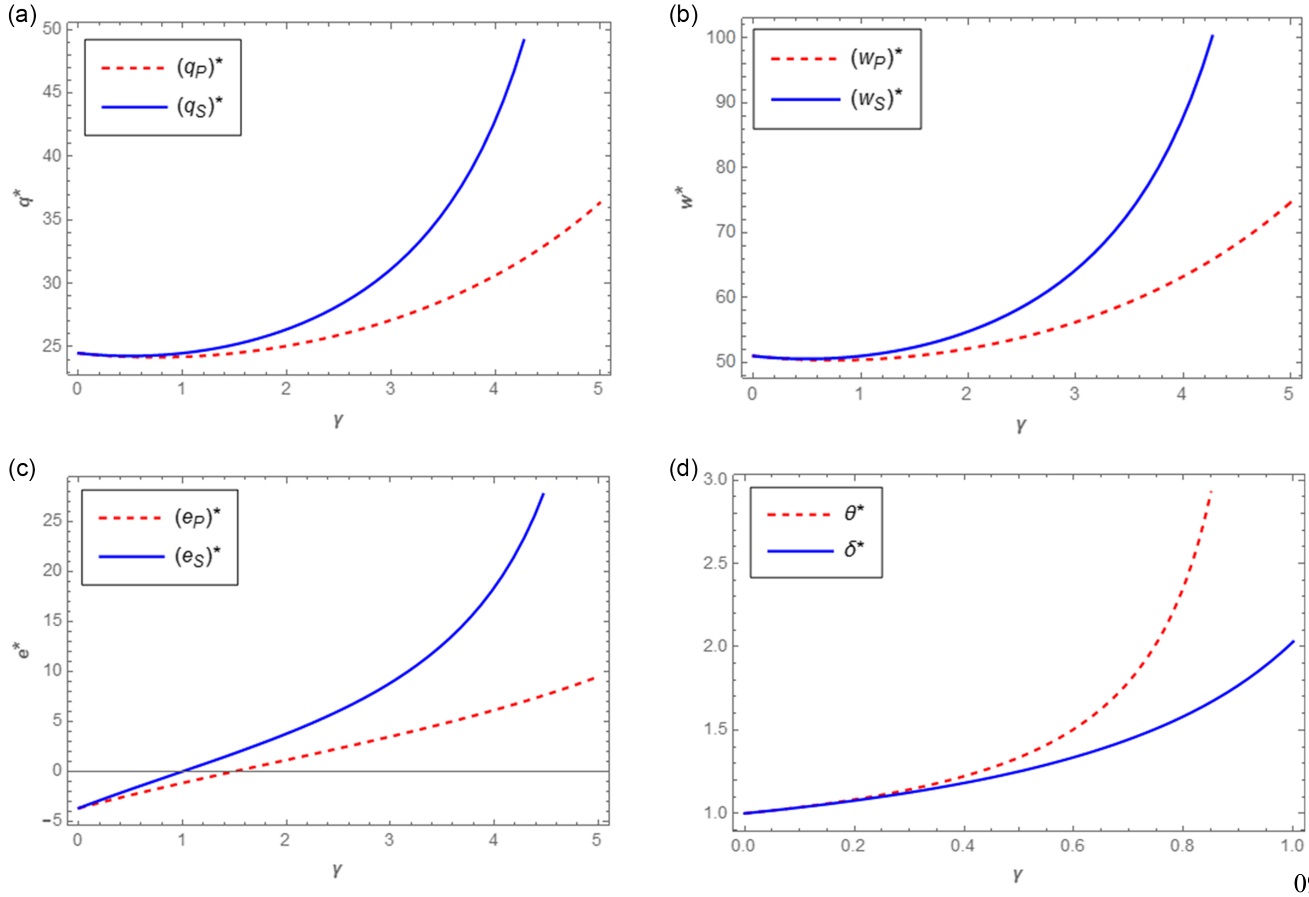
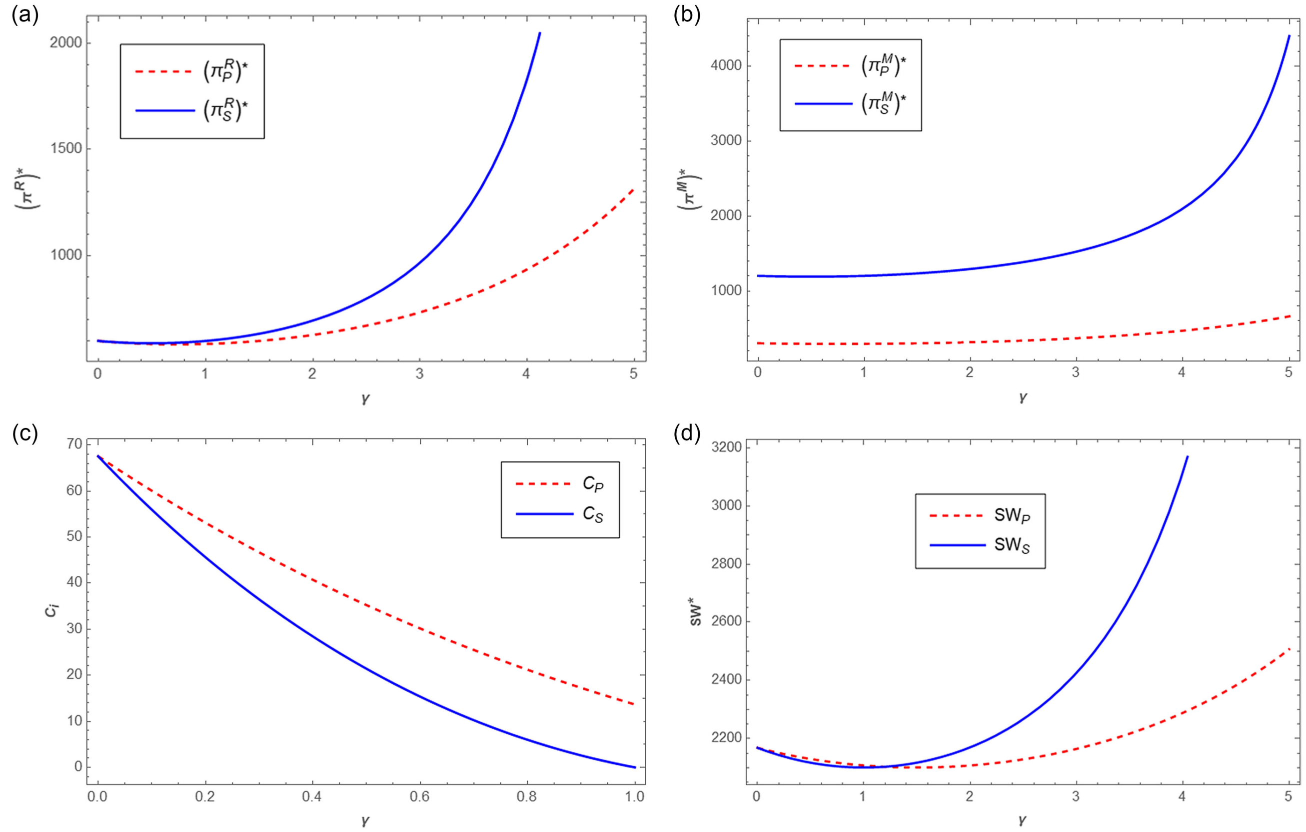


Figure 6
Impact of γ on (a) the retailer's profit, (b) the manufacturer's profit, (c) expenditures for corresponding policies, and (d) social welfare



selection process focuses on applicability at various phases and the cultivation of market preferences.

As mentioned previously, the findings continue to indicate that policies are influenced by the specific beneficiary group and the level of advancement in the industry's transition toward sustainability. This entails prioritizing the provision of incentives to banks during the initial stages of transition in regions with greater risks associated with green investments, as well as offering direct subsidies to entrepreneurs who face significant financial challenges in adopting environmentally friendly practices.

7. Conclusion and Discussion

7.1. Discussion of managerial implications

Performance-based incentives and interest subsidy policy for green credit are widely implemented with numerous favorable outcomes. The impact of the two subsidy policies on environmental performance and operational decisions is different. Meanwhile, the subsidy ratio deeply reflects the effectiveness of the subsidy policy. However, there is limited theoretical research that compares the implications of green credit incentives in operational management field [48, 8]. Motivated by the above facts, our paper explores the impacts of the two policies, specifically how incentives for the bank influence the emission investments and operational decisions of the supply chain. In this paper, we derived game-theoretic models to analyze the optimal decisions under both incentives. We first characterized the effect of the incentives of the supply chain. Then, we compared both incentives from different perspectives and analyzed the driving factors. Moreover, we derive the optimal support ratio with the objective of maximizing the social welfare. Our results show that under consumer green preferences, subsidy policies help amplify market demand for green goods. Although both policies have desirable effects, the mechanism of action differs depending on the direct beneficiaries. The results and managerial implications are as follows:

- On the policymaker's side, the choice between the two policies should consider two factors: the stage of green transformation of industries as well as green credit development, the degree of environmental damage and consumer awareness of environmental protection. For the initial issue, interest subsidy policy is more effective to manufacturers with higher financial burdens in emission reduction investments. In the meanwhile, performance-based incentives policy is more appropriate to encourage banks to grant green loans as it helps them to mitigate credit risks. In choosing which subsidy policy to adopt, the government could consider the environmental value after emission reduction, as well as the environmental damage and consumer green awareness.
- For the supply chain players, side, both the incentive policy increases the optimal operational decisions and economic profits. Both the subsidy policies could also reduce the financial costs of the green loan in varying degrees and ways. While the manufacturer prefers interest subsidies policy than performance-based incentives because the former can actively increase the abatement efforts because the costs are reduced. This suggests the

government to provide subsidies to the manufacturer when they are not motivated to reduce emissions under higher financial burdens.
- On the bank's side, the decision to grant green loans by the bank depends on the possible risk and return of the emission reduction investments. The bank prefers the performance-based incentives as it compensates parts of the risk of the green loans. However, the banking sector should also fulfill social responsibility by trying to offset the interest on green credit with high performance incentives.

7.2. Conclusion and future work

There are several directions for future research. In this study, all members are all risk neutral while risk appetite exists. Thus, it is important to investigate how risk attitudes of the bank as well as the supply chain players affect the operational decisions. Moreover, in our model, we suppose the supply chain members maximizing their profits with economic goal. While green credit subsidies also help to increase the social responsibility of supply chain members, it is valuable to investigate the optimal support strategy under different government's goal. In this direction, the government may concurrently adopt various incentive polices, and the goal may consider increasingly complicated situations. Another further research direction is to investigate other subsidy strategies to mitigate banks' credit risk commonly used in practice [49, 50, 51].

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Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

All data generated or analyzed during this study are included in this study.

Author Contribution Statement

Keyu Zhan: Methodology, Software, Investigation, Data curation, Writing – review & editing, Visualization, Supervision, Project Administration. **Dongxiu Wu:** Conceptualization, Validation, Formal analysis, Resources, Writing – original draft, Funding acquisition.

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