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IMPACTS OF INFORMATION SHARING ON A GREEN SUPPLY CHAIN WITH BANK CREDIT FINANCING

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Abstract. This paper investigates the impacts of information sharing on a green supply chain in which a capital-constrained manufacturer is endowed with private demand information. In different information sharing scenarios (no information sharing, partially sharing information with either the supplier or the bank, and public information sharing), the manufacturer invests in carbon emission reduction and determines the optimal output after gaining a loan from a bank by pledging carbon emission permits. Interestingly, we find that publicly sharing positive demand signals can either enhance or decrease the output and emission abatement level. Additionally, we find that the pledge rate becomes deterministic when sharing positive information. In contrast, it is variable and no larger than in the no-information-sharing scenario when sharing negative information. There is a case in which public information sharing benefits the manufacturer and supplier, regardless of sharing positive or negative information. Contrary to our intuition, we find that while the bank suffers from publicly sharing positive information, it can benefit from sharing negative information. Moreover, this study provides the specific conditions under which a manufacturer chooses a particular type of information sharing format.

Mathematics Subject Classification. 91B06, 91B38, 91B76.

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1. Introduction

Considerable evidence indicates that global temperatures are rising at an unprecedented rate, mainly due to greenhouse gas emissions. The International Energy Agency reported that carbon emissions reached an all-time high of 37.4 billion tons in 2023 [24]. The consequent climate change and environmental disasters have attracted widespread public attention, and the world has reached a broad consensus on reducing carbon emissions to combat climate change. From the United Nations Framework Convention on Climate Change in 1992 to the Kyoto Protocol in 1997 and the Paris Agreement in 2015, countries that have signed the agreements have committed to achieving their emission reduction targets [6]. Consequently, coordinating economic development and reducing carbon emissions have become the focus of society, and authorities thus take measures to curb carbon emissions. For example, the Chinese government has established regulations on enterprises' emissions,

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Keywords. Information sharing, carbon emission permit, carbon emission reduction, bank credit, pledge rate.

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requiring those that fail to meet carbon emission reduction standards to shut down[1]. In 2020, the Chinese government announced its goal of achieving a carbon peak by 2030 and carbon neutrality by 2060[2].

Under enormous governmental pressure and growing public awareness of environmental concerns, enterprises make significant efforts, such as investing in low-carbon technologies, to continue operating [17, 32]. In this scenario, enterprises may not only face operating-induced capital constraints, such as purchasing raw materials, but also lack the capital to invest in green technology innovation or acquire waste-processing equipment [1, 23]. For example, Dongling Group Co., Ltd. (abbreviated hereafter as Dongling), engaged in manufacturing construction steel and zinc products, was one of Chinas top 500 companies in 2022. In 2021, the CEO of this corporation announced that the company would focus on green and healthy development in the future[3]. However, Dongling faces a bankruptcy risk due to capital constraints and substantial debts in 2024. Nowadays, it is unable to operate normally, let alone invest in green development[4]. Capital constraints also exist in the new energy vehicle industry. For instance, Fisker Inc. (abbreviated hereafter as Fisker) is an American electric vehicle manufacturer. In 2023, the companys net loss reached US$ 761.9 million, with a loss of US$ 2.22 per share. Fisker submitted a bankruptcy protection application in June 2024[5]. Evidently, it lacks sufficient funds to invest in green technology and reduce carbon emissions. Many companies worldwide are facing similar problems. During the World Green Economy Summit held in Dubai in October 2024, Mahmoud Fathallah, Director of the Environmental and Meteorological Affairs Management Bureau of the Arab League, stated that funding shortage was one of the most daunting challenges confronting most Arab countries in transitioning to a green economy[6].

Nevertheless, the good news is that carbon emission permits, as a form of intangible assets, can be traded in carbon markets. China officially opened its national carbon trading market in July 2021. Enterprises can sell (buy) carbon emission permits in the market. This not only serves as an important measure to address climate change and reduce greenhouse gas emissions, but also provides enterprises with an effective way to generate profits by utilizing carbon assets. In addition to supporting the sustainable development of enterprises and carbon emission reduction, banks are willing to provide green loans to enterprises that pledge carbon assets as security. For example, Everbright Bank Co., Ltd. issued a loan of 40 million RMB pledged by carbon emission permits to Hongsheng Electric Heating Company of Jiugang Group[7]. In April 2024, HSBC Bank (China) Company Limited provided sustainable supply chain financing projects for Saint Gobain Group of France, a multinational corporation engaged in producing safety glass, gypsum building materials, and so on[8]. Although bank financing by pledging carbon emission permits has been used in practice, few studies have focused on the role of carbon assets as collateral in supply chain financing, especially considering information asymmetry.

In practice, information crucially affects firms' decisions and plays an important role in supply chain operations [14, 44, 47]. The successful running of material and financing flows highly depends on information flow [9, 19, 32]. More firms, such as Dell and Amazon, focus on data collection and analysis [12, 42]. However, many enterprises remain unclear about market demand information and consumers preferences due to continuous upgrading, product seasonality, and complicated changing market environments [20]. This may lead not only to a mismatch between supply and demand but also to low service levels, which are detrimental to enterprises. For example, Nippon Steel & Sumitomo Metal Corporation is a Fortune 500 company engaged in the steel industry. It closed Kure Works in Hiroshima Prefecture, western Japan, in 2020 due to a mismatch between supply and demand, resulting in a net loss of US$4 billion[9]. Wayfair, an American e-commerce company with

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[1] `http://china.cnr.cn/gdgg/20170714/t20170714_523850712.shtml`.

[2] `http://www.gov.cn/xinwen/2021-04/22/content_5601515.htm`.

[3] `https://www.esgc.cc/news/show-8053.html`.

[4] `https://caifuhao.eastmoney.com/news/20240829234024063830490`.

[5] `https://baijiahao.baidu.com/s?id=1802249653365065281&wfr=spider&for=pc`.

[6] `https://www.thepaper.cn/newsDetail_forward_28947729`.

[7] `http://www.tanpaifang.com/tanzichanguanli/2022/0929/90979.html`.

[8] `http://www.tanpaifang.com/tanjinrong/2024/0424/105944.html`.

[9] `https://www.sohu.com/a/371867636_777309`.

great influence, reported that its net loss exceeded US$ 78 million in the first half of 2021 because of decreased market demand [5]. Information sharing is an important approach toward alleviating this problem [21]. With advances in information technology, it has become a common phenomenon for companies to share information with their partners in the supply chain [3]. For example, Apple shared information about the iPhone 13 with Lens Technology Co., Ltd. Hewlett-Packard (HP)[10], as a computer manufacturer, also shared market information with Intel on processors and chipsets to promote computer upgrades. Under the global trend of low-carbon development, information sharing also affects firms decisions in a green supply chain. They must adjust their carbon emission reduction levels and pricing strategies [2,53]. Moreover, when considering a capital-constrained manufacturer that obtains loans from a commercial bank by pledging carbon emission permits, the information sharing formats encompass no information sharing, partial information sharing with the bank or upstream firm, and public information sharing. These information-sharing formats evidently result in different operational decisions and performances. However, it remains unclear how such information-sharing formats affect each members decision and profit in a green supply chain with a capital-constrained manufacturer.

Based on the above analysis, this study aims to fill the gap in the literature by addressing the following issues: First, how does each participant make decisions in green supply chain financing under different information sharing formats? Second, how do information and information sharing formats affect a capital-constrained manufacturers production and carbon emission reduction decision? Third, What is the impact of information sharing formats on the pledge rate when carbon assets are used as collateral? Fourth, Does there exist a range in which information sharing results in a Pareto improvement?

To address these problems, we build a model comprising a supplier and a capital-constrained manufacturer that produces items and invests in carbon emission reduction after obtaining a loan from a commercial bank by pledging carbon emission permits. The manufacturer is endowed with private demand information, which may be a positive or negative signal. Contrary to conclusions in previous literature [11,29], the result shows that both the optimal output and carbon emission abatement level in the bankruptcy scenario are higher than those in the no bankruptcy scenario when the manufacturer faces bankruptcy risk and the signal value is relatively small, regardless of the type of information sharing mode. It also shows that partially sharing positive information guarantees the manufacturer achieving optimal output and carbon emission reduction by inducing the bank to offer a constant pledge rate; however, publicly sharing positive information may enhance or lower the output and emission abatement level under certain conditions. Additionally, it shows that the wholesale price in the no-information-sharing scenario is higher than those in the partial and public information-sharing scenarios if the distance between high and low demand is small, regardless of sharing positive or negative information. Regarding the impact of information sharing on pledge rate, if the bank receives a favorable signal, the pledge rate is deterministic; otherwise, the pledge rate in no information sharing scenario is the largest. For the impacts of information sharing on profit, partial and public information sharing benefit the manufacturer and supplier if the distance between high and low demand is large, regardless of the capital-constrained manufacturer facing bankruptcy risk or not. Contrary to our intuition, the bank suffers from publicly sharing positive information because of the decreased pledge rate, but benefits from negative information sharing because of the lowered bankruptcy risk. The type of information sharing format chosen by the manufacturer depends on the disparity between the high- and low-demand states and the prior belief in the high-demand state.

The remainder of this paper is organized as follows: Section 2 reviews the related literature. Section 3 analyzes the equilibria under different information sharing formats. Section 4 describes the impact of information sharing on the optimal decisions and profits of each member. Section 5 focuses on numerical analyses to illustrate the impacts of some key factors. Section 6 presents some managerial implications. Section 7 concludes the paper and provides some directions for future research.

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[10] `https://www.nbd.com.cn/articles/2021-09-22/1921199.html`.

2. LITERATURE REVIEW

2.1. Green supply chain

This study is most closely related to the literature on green supply chain management. Government-regulated firms take certain steps, such as designing green products and investing in emission reduction technology, to lower the impact of production and operations. Bai *et al.* [4] establish a supply chain framework comprising one manufacturer and two retailers, wherein the manufacturer endeavors to reduce carbon emissions. Ouardighi *et al.* [37] investigate how double marginalization influences the carbon emission abatement associated with pollution accumulation in a green supply chain. Kang and Tan [28] examine how firms make carbon emission reduction decisions using an evolutionary game model. Dye and Hsieh [16] suggest that low-carbon innovation simultaneously improves the retail price and enhances the order quantity. Ghosh and Shah [18] study participants optimal decisions and the products green levels in settings with different supply chain structures. Yang *et al.* [50] discuss the impact of a retailers fairness concern on green products.

Some firms also make costly efforts to reduce carbon emissions, driven by consumers' growing eco-awareness and the pursuit of increased profits. Wang and Choi [45] explore firms production and emission decisions in a demand uncertainty market considering carbon emission limitations. Peng *et al.* [39] discuss firms competition and cooperation strategies in green marketing promotion, considering customer satisfaction. Mardyana and Mahata [35] investigate how carbon emission reduction technology affects firm and environmental performance. They suggest that dual carbon emission technology is more effective in improving consumer demand. Wang and Sun [46] model a dual-channel supply chain and find that a manufacturer is willing to produce low-carbon items when the direct sales volume is high. Liu *et al.* [32] study the emission reduction issue in an agricultural supply chain and find that supply chain performance is enhanced when manufacturers and retailers cooperate in terms of emission reduction. Parsaeifar *et al.* [38] establish a three-echelon supply chain in which agents compete vertically and horizontally, and they find that economic performance increases with the intensity of carbon emission reduction.

In line with the aforementioned papers, we also study carbon emission reduction issues driven by consumers low-carbon awareness under government environmental policies in a green supply chain. However, our work differs from previous studies in at least two respects. On the one hand, in our study, the manufacturer that invests in carbon emission reduction faces capital constraints and borrows from a commercial bank. The manufacturer may also go bankrupt owing to failure to repay the loan. On the other hand, carbon emission permits can be pledged to obtain a loan from a bank, besides being traded in a carbon market.

2.2. Supply chain financing

Another stream of the related literature focuses on supply chain financing, especially bank credit financing. The relevant literature includes research on production (inventory) strategies, impacts of capital on a firms replenishment strategy and profit, supply chain coordination, and supply chain financing channel adoption. Dada and Hu [15] examine how a capital-constrained firm makes an inventory strategy in multiple periods under bank financing. Ries *et al.* [41] discuss the influence of financial conditions on a retailers ordering decision and payment strategy. Chen [12] shows the effectiveness of a revenue-sharing contract on supply chain coordination when a capital-constrained firm adopts both bank and trade credit. Yan *et al.* [48] explore the supply chain coordination conditions when a supplier offers a guaranteed contract to a bank. Kouvelis and Zhao [29] suggest that a combined contract can achieve supply chain coordination under bank credit financing.

Some researchers have also compared different financing methods. Jing and Seidmann [27] model a supply chain comprising a manufacturer and a capital-constrained retailer, and they suggest that trade credit brings more profit than bank credit for a supply chain when a firms production cost is relatively low. Yang *et al.* [49] investigate how risk aversion influences a firms financing strategy and show the specific conditions under which bank or trade credit should be adopted. Chen *et al.* [13] compare crowdfunding, trade credit, and bank credit, and they show the conditions under which a specific financing method should be adopted. Jena *et al.* [25]

compare trade credit, factoring, and reverse factoring, and they suggest that reverse factoring is more beneficial for capital-constrained manufacturers. Zhao *et al.* [54] study how a firm chooses a financing mode when resuming operations, and they find that two-stage bank credit financing works better for the firm. Lu *et al.* [33] suggest that when accessing platform and bank financing, firms still choose bank financing, notwithstanding the high bank interest rate.

Our work differs from the aforementioned studies in the following aspects: First, we assume that the capital-constrained manufacturer invests in carbon emission abatement under the carbon emission regulation policy. Second, in the present study, the manufacturer obtains loans from a bank by mortgaging carbon emission permits instead of tangible assets. Another key difference is that the capital-constrained manufacturer is endowed with superior demand information and decides on the information sharing format: none, partial, or public information sharing. Additionally, we explore the role of bank credit in determining the information sharing format.

2.3. Information sharing

Our paper is also related to the literature on information sharing. Most studies focus not only on the incentive for downstream firms to share information with upstream firms but also on the information-sharing behavior [34,44]. Li and Zhang [31] find that a retailer shares information voluntarily with its manufacturer when market demand uncertainty is not large. Ha *et al.* [22] model two competing supply chains and show that information sharing highly depends on manufacturers efficiency in cost reduction. Shamir and Shin [44] demonstrate that a retailer is willing to publicly share information because high-demand information sharing ensures large product capacity, while low-demand information sharing can deter a competitors entry. Zhang and Nault [52] suggest that a manufacturer shares information with its supplier when the suppliers production load is relatively small. Liu *et al.* [32] investigate the information sharing issue in an e-tailing supply chain and show that an e-retailer voluntarily shares demand information when the freshness coefficient is relatively large. Lusiantoro *et al.* [34] investigate the impact of information sharing on supply chain performance, considering that the products are perishable. Yu *et al.* [51] show that information sharing helps store brands encroach on the reselling mode. Researchers also pay attention to the scenario in which an upstream firm shares information with a downstream firm. For instance, Bodendor and Franke [7] discuss the impact of one- and two-sided information sharing on supply chain performance.

The issue of information sharing in a low-carbon supply chain has also been discussed. For example, Zhang *et al.* [53] suggest that a retailer may choose to share information fully or partially with a manufacturer that conducts green innovation. Kovtun *et al.* [30] explore whether firms have the incentive to share individual demand orders. Sarkar and Guchhait [43] suggest that sharing asymmetric information does not benefit all members in a green supply chain. In contrast to these works, we study information sharing in a supply chain in which a manufacturer is capital-constrained yet has an information advantage. Additionally, we focus on the impacts of different information-sharing formats on bank credit and carbon emission reduction in environmental regulation settings.

2.4. Contributions of this paper

The contributions of this study are presented as follows: First, the related literature on green supply chains focuses on carbon emission reduction decisions and the impacts of carbon emission regulations with symmetric information [16, 28, 32, 35, 37], whereas we explore asymmetric information and information sharing formats. We investigate the relationship between optimal carbon emission reduction decisions and information sharing formats. The findings show that publicly sharing positive information improves carbon emission reduction, whereas sharing negative information publicly may lower carbon emission reduction levels under certain conditions. Second, contrary to the previous literature on supply chain financing [12,25,29,33,41,48], we investigate how a commercial bank determines the pledge rate when carbon emission permits serve as pledged subjects. We find that the pledged ratio highly depends on the carbon price, demand signal, and bankruptcy risk faced by the manufacturer. Third, unlike studies on asymmetric information [7,22,32,34,43,51,52], we explore how a capital-constrained manufacturer chooses an information sharing format. The findings indicate that when the distance between high and low demand is small, the manufacturer should either partially share information with the supplier or publicly disclose it.

3. Model analysis

3.1. Model description

We model a supply chain in which a supplier (she) sells material to a capital-constrained manufacturer (he) endowed with private demand information. The supplier decides on the wholesale price w to maximize her profit. The manufacturer produces products and invests in carbon emission reduction after obtaining a loan from a bank by pledging carbon emission permits. The bank then determines the pledge rate. Under the carbon cap-and-trade system, the capital-constrained manufacturer can sell (buy) the surplus (deficient) carbon emission permits in the carbon trading market to accrue profit (cost). When the manufacturer can repay the principal and interest of the bank loan, there is no bankruptcy risk; otherwise, the manufacturer faces bankruptcy risk and transfers all the remaining sales income to the bank at the end of the sales season. Considering consumers' low-carbon preferences, they are willing to pay higher prices for green products. Thus, the inverse demand function is written as $p = A + \theta - q + a\varepsilon$ [31, 53], where A is the stochastic market demand. To facilitate the analysis, we assume that A obeys a two-point distribution, taking A_{H} (A_{L}) as the high (low) demand with possibility $r(1-r)$. Let $u = rA_{\mathrm{H}} + (1-r)A_{\mathrm{L}}$ denote mean demand value; θ represents the disturbance factor, taking θ_0 with a possibility of $1/2$ and $-\theta_0$ with a possibility of $1/2$. The distributions of A and θ are common knowledge to all members, whereas only the manufacturer can observe the exact value of θ, which is private information. Moreover, a represents consumers' sensitivity to carbon emission reduction.

With asymmetric information, first, the manufacturer observes the market demand signal and then decides whether to share it or not. Second, the supplier offers the wholesale price. If the manufacturer does not share information, the supplier infers the manufacturer's quantity based on prior probability and decides the wholesale price. Third, the bank decides on an appropriate pledge rate to maximize its profit and control risk. The manufacturer pledges a certain number of carbon emission permits to obtain a loan from the bank. Let B be the manufacturer's initial capital, and V be the number of pledged carbon emission permits. After receiving the loan, the manufacturer buys resources from the supplier and decides on the production quantity q, while investing in carbon emission reduction at a cost of $\frac{\tau\varepsilon^2}{2}$. The quadratic cost function captures the character of the diminishing return of emission abatement investment, which is widely adopted in the related literature (see [1, 36, 40]); τ indicates the manufacturer's efficiency in reducing carbon emissions. A higher τ means a lower efficiency in reducing carbon emissions. Thereafter, the manufacturer sells products at price p in the market and sells (buys) excessive (inadequate) carbon emission permits in the carbon market at price p_c. Finally, he repays the bank loan by using the sales revenue from the product market and the carbon trading market. If the manufacturer is unable to pay off the loan principal and interest, the bank has the right to dispose of the pledged carbon emission permits and obtain the sales revenue transferred from the manufacturer. The sequence of events is depicted in Figure 1.

In this paper, the superscript $K = N, \mathrm{PS}, \mathrm{PB}$, and S denotes the no information sharing, partially sharing information with the supplier, partially sharing information with the bank, and public information sharing scenario, respectively; the superscript $x = 1, 2$ indicates observing positive or negative signals, respectively; and the subscript $j = s, b$, and m refers to the supplier, bank, and manufacturer, respectively. For example, q_m^{N1} represents the manufacturer's production quantity in no information sharing scenario when observing a positive signal, q_s^N is the manufacturer's production quantity inferred by the supplier in the no information sharing scenario, and π_j^K is the expected profit of participant j under information status K. The relevant notations are described in the following.

Some assumptions are presented thus:

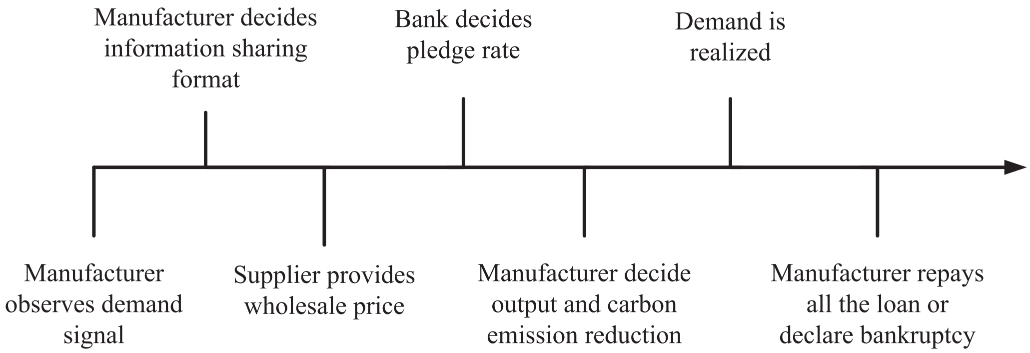

FIGURE 1. Sequence of events.

TABLE 1. Notations.

Notations	Meaning
Superscript/subscript	
$K = N, \mathrm{PS}, \mathrm{PB}, S$	Superscript to represent the information sharing format (N = no information sharing, PS/PB = partially sharing information with the supplier/bank, S = public information sharing)
$x = 1, 2$	Superscript to indicate the cases with or without bankruptcy risk (1 =the case without bankruptcy risk, 2 = the case with bankruptcy risk)
$i = \mathrm{H}, \mathrm{L}$	Subscript to represent the demand state (H = high-demand state, L =low-demand state)
Decision variables	
w	Wholesale price offered by the supplier
Q	Manufacturer's output
ε	Carbon emission reduction level
Other parameters	
p	Retail price per unit product
$A_i (i = \mathrm{H}, \mathrm{L})$	Market potential
R	Probability of high-demand state
B	Manufacturer's initial capital
e_0	Carbon emission per unit product
G	Initial carbon quota
γ^{K^*}	The final pledge rate
γ	Pledge rate
C	Supplier's product cost per unit item
p_c	Carbon emission trading price
A	Consumers' sensitivity coefficient to emission reduction
θ_0	Disturbance signal
τ	Cost coefficient of carbon emission reduction
V	Pledged number of carbon emission permits

Assumption 1. *In the low-demand state, when observing θ_0, the manufacturer does not face any bankruptcy risk, whereas when observing $-\theta_0$, it goes bankrupt. The manufacturer does not confront any bankruptcy risk in the high-demand state, regardless of observing θ_0 or $-\theta_0$. Therefore, this hypothesis is reasonable because if the manufacturer goes bankrupt in high and low demand while observing a favorable market signal, it will give up production and quit the market. Thus, we assume that the manufacturer faces bankruptcy risk when observing unfavorable signals in the low-demand state. A similar assumption is also employed by Jiang et al. [26].*

Assumption 2. *Similar to Boyabatli and Toktay [8], we assume that the bank decides on the pledge rate according to the value of the collateral. If the manufacturer pledges* V *units of carbon emission permits, the value of the pledged carbon asset is* Vp_c*, where* p_c *is the trading price of the carbon emission permits. Hence, given pledge rate* γ*, the manufacturer's loan size is* $\gamma V p_c$*.*

Assumption 3. *Assume that the production cost per unit product is* c_m*. This fixed production cost does not substantially affect every party's decision. To highlight the research topic and simplify the calculations, we consider only the manufacturer's ordering cost, assuming that the production cost is zero. A similar assumption is adopted by Cao and Yu [10].*

Assumption 4. *Assuming that the manufacturer is not a speculator, there exists* $wq + \frac{\tau\varepsilon^2}{2} - B = \gamma p_c V$*. Put differently, the manufacturer uses all the loan in production and carbon emission reduction [13, 25].*

3.2. Equilibrium analysis in the no information sharing scenario

This subsection analyzes the benchmark case in which the manufacturer does not share information with any member. According to the value of θ, there are two possible scenarios. When observing θ_0, the manufacturer faces no bankruptcy risk even the in low-demand state. Respectively, denote q_m^K and $\varepsilon_m^K (K = N, \mathrm{PS}, \mathrm{PB}, S)$ as the output and carbon emission reduction that can optimize the manufacturer's profit. In this scenario, the manufacturer's expected profit is

$$\begin{aligned}\pi_m^{N1} &= r\left(A_{\mathrm{H}} + \theta_0 - q_m^{N1} + a\varepsilon_m^{N1}\right) q_m^{N1} + (1-r)\left(A_{\mathrm{L}} + \theta_0 - q_m^{N1} + a\varepsilon_m^{N1}\right) q_m^{N1} \\ &\quad - \left(w^N q_m^{N1} + \frac{\tau\varepsilon_m^{N12}}{2} - B\right)(1+R) - p_c\left[e_0\left(1-\varepsilon_m^{N1}\right) q_m^{N1} - G\right] - B.\end{aligned} \tag{1}$$

In equation (1), $(w^N q_m^{N1} + \frac{\tau\varepsilon_m^{N12}}{2} - B)(1+R)$ is the loan principal and interest that the manufacturer needs to repay at the end of the sales season, and $p_c[e_0(1-\varepsilon_m^{N1})q_m^{N1} - G]$ is the sales revenue or cost of carbon assets in the carbon trading market. The next proposition characterizes the manufacturer's optimal production quantity and carbon emission reduction when observing a favorable demand signal θ_0.

Proposition 1. *When observing* θ_0*, the optimal production quantity is* $q_m^{N1^*} = \frac{\tau(1+R)\left(u+\theta_0-w^N-w^N R-p_c e_0\right)}{2\tau(1+R)-(p_c e_0+a)^2}$ *and the optimal carbon emission reduction level is* $\varepsilon_m^{N1^*} = \frac{(p_c e_0+a)\left(u+\theta_0-w^N-w^N R-p_c e_0\right)}{2\tau(1+R)-(p_c e_0+a)^2}$*. Both decrease with* $\tau, R,$ *and* w *and increase with* $u, \theta_0,$ *and* a*. However,* $\varepsilon_m^{N1^*}$ *increases with* p_c*, and the relationship between* $q_m^{N1^*}$ *and* p_c *is uncertain.*

From Proposition 1, we can see that the optimal production quantity decreases with the cost coefficient of carbon emission reduction τ, interest rate R, and wholesale price w, while it increases with the mean demand u, signal value θ_0, and consumers' low-carbon sensitivity a. The larger the cost coefficient of carbon emission reduction, the more capital the manufacturer invests to achieve the emission reduction goal, which will crowd out the capital for production. Consequently, the optimal production quantity decreases with τ. A higher interest rate increases the manufacturer's financing cost. As a result, the manufacturer needs to control the loan size by reducing the production quantity. In terms of low-carbon awareness, a larger a means that consumers are willing to pay higher prices for low-carbon products, which encourages the manufacturer to enhance production quantity. However, the relationship between $q_m^{N1^*}$ and carbon price p_c is uncertain. When the carbon trading price p_c is relatively small and the selling price per unit product is sufficiently high to cover the carbon trading cost, the output increases with p_c. When p_c is relatively high, the revenue obtained by selling a unit product is less than the carbon trading cost per unit product, and the manufacturer cuts off the production quantity. The relationship between $\varepsilon_m^{N1^*}$ and other parameters can be analyzed similarly. We find that $\varepsilon_m^{N1^*}$ increases with p_c. This is because a high carbon trading price, on the one hand, ensures that the manufacturer gains more profit by selling emission permits in the carbon market; on the other hand, it helps the manufacturer obtain more production capital by pledging carbon emission permits. As a result, the manufacturer is motivated to reduce more carbon emissions with a high p_c. The findings also indicate that carbon emission regulations are not always detrimental to firms; they can also benefit them.

When the manufacturer observes $-\theta_0$, it can repay all the loan principal and interest in a high-demand state. However, an unfavorable signal further lowers the expected market demand in a low-demand state, which may result in the manufacturer's failure to repay the loan. In this case, the manufacturer declares bankruptcy, transfers the sales revenue, and pledges assets to the bank. Denote the production quantity as q_m^{N2} and the emission abatement level as ε_m^{N2} in this scenario. With disturbance signal $-\theta_0$, the manufacturer's expected profit is

$$\begin{aligned}\pi_m^{N2} = r\Bigg[&\left(A_{\mathrm{H}} - \theta_0 - q_m^{N2} + a\varepsilon_m^{N2}\right) q_m^{N2} - \left(w^N q_m^{N2} + \frac{\tau\varepsilon_m^{N22}}{2} - B\right)(1+R) \\ &- p_c\left(e_0\left(1-\varepsilon_m^{N2}\right) q_m^{N2} - G\right)\Bigg] - B.\end{aligned} \tag{2}$$

The next proposition describes the manufacturer's optimal decisions when observing an unfavorable signal $-\theta_0$.

Proposition 2. *When observing $-\theta_0$, the optimal output is $q_m^{N2^*} = \frac{\tau(1+R)(A_{\mathrm{H}}-\theta_0-w^N-w^N R-p_c e_0)}{2\tau(1+R)-(p_c e_0+a)^2}$, and the optimal emission reduction is $\varepsilon_m^{N2^*} = \frac{(p_c e_0+a)(A_{\mathrm{H}}-\theta_0-w^N-w^N R-p_c e_0)}{2\tau(1+R)-(p_c e_0+a)^2}$.*

Proposition 2 shows that the manufacturer's optimal decision is closely related to highdemand A_{H} and the disturbance signal $-\theta_0$, yet it is immune to the mean demand u. Interestingly, we find that when the manufacturer confronts bankruptcy risk and $\theta_0 < \frac{A_{\mathrm{H}}-u}{2}$. Both the optimal output and carbon emission abatement level are higher than those in the no-bankruptcy scenario. When θ_0 is relatively small, *i.e.*, $\theta_0 < \frac{A_{\mathrm{H}}-u}{2}$, the manufacturer that undertakes limited repayment liability tends to produce more items to meet consumers' high demand in the bankruptcy scenario. Meanwhile, he also prefers to invest in a high level of abatement to increase marginal revenue. When $\theta_0 > \frac{A_{\mathrm{H}}-u}{2}$, the real market demand is very low, even in the high-demand state. Consequently, the manufacturer tends to lower the output and reduce the investment effort in abating carbon emissions in the bankruptcy scenario.

The bank balances its profit and risk by determining the optimal pledge rate. It makes decisions based on the prior possibility of signal θ because it cannot observe the disturbance signal. As we know, the manufacturer goes bankrupt only when the disturbance signal is $-\theta_0$ and the demand is low. Thus, the bank can recover the loan principal and interest with possibility $(1+r)/2$, and gets transfer revenue at the end of sales season with possibility $(1-r)/2$. Denote q_b^K and $\varepsilon_b^K (K = N, \mathrm{PS}, \mathrm{PB}, S)$ as the output and carbon emission reduction inferred by the bank, respectively. Then,

$$\begin{aligned}\pi_b^N = {}& \frac{1-r}{2}\left[\left(A_{\mathrm{L}} - \theta_0 - q_b^N + a\varepsilon_b^N\right) q_b^N - p_c\left(e_0\left(1-\varepsilon_b^N\right) q_b^N - G\right)\right] \\ &+ \frac{1+r}{2}\left(w^N q_b^N + \frac{\tau\varepsilon_b^{N2}}{2} - B\right)(1+R) - \left(w^N q_b^N + \frac{\tau\varepsilon_b^{N2}}{2} - B\right).\end{aligned} \tag{3}$$

In equation (3), $(A_{\mathrm{L}} - \theta_0 - q_b^N + a\varepsilon_b^N)q_b^N - p_c(e_0(1-\varepsilon_b^N)q_b^N - G)$ indicates the revenue transferred from the manufacturer in the bankruptcy scenario; $(w^N q_b^N + \frac{\tau\varepsilon_b^{N2}}{2} - B)(1+R)$ represents the loan principal and interest recovered in the no bankruptcy scenario.

The bank optimizes its expected profit by choosing

$$q_b^{N^*} = \frac{\tau(1-r-rR-R)\left[(1-r)\left(A_{\mathrm{L}} - \theta_0 - p_c e_0\right) - w^N(1-r-rR-R)\right]}{(1-r)\left[2\tau(1-r-rR-R) - (1-r)\left(p_c e_0 + a\right)^2\right]} \tag{4}$$

$$\varepsilon_b^{N^*} = \frac{\left(p_c e_0 + a\right)\left[(1-r)\left(A_{\mathrm{L}} - \theta_0 - p_c e_0\right) - w^N(1-r-rR-R)\right]}{2\tau(1-r-rR-R) - (1-r)\left(p_c e_0 + a\right)^2}. \tag{5}$$

Then, the optimal pledge rate $\gamma_b^{N^*}$ satisfies $\gamma_b^{N^*} p_c V = w^N q_b^{N^*} + \frac{\tau \varepsilon_b^{N^*2}}{2} - B$.

Whether $\gamma_b^{N^*}$ is the final pledge rate depends on the manufacturer's output and the emission reduction level. Denote ${\gamma_m}^{K1^*}$ and ${\gamma_m}^{K2^*} (K = N, \mathrm{PS}, \mathrm{PB}, S)$ as the pledge rate that can realize the manufacturer's output in the no bankruptcy and bankruptcy scenarios, respectively. The following equations hold:

$$\gamma_m^{N1^*} V p_c = w^N q_m^{N1^*} + \frac{1}{2} \tau \varepsilon_m^{N1^*2} - B, \gamma_m^{N2^*} V p_c = w^N q_m^{N2^*} + \frac{1}{2} \tau \varepsilon_m^{N2^*2} - B. \tag{6}$$

Denote γ^{K^*} as the final pledge rate, as mentioned in Table 1. By comparing $\gamma_b^{N^*}$ to ${\gamma_m}^{N1^*}$ and ${\gamma_m}^{N2^*}$, we can establish the next proposition.

Proposition 3. *When the signal is θ_0, if $\gamma_b^{N^*} \geq {\gamma_m}^{N1^*}$, the manufacturer can realize his optimal output and $\gamma^{N^*} = {\gamma_m}^{NI^*}$; otherwise, $\gamma^{N^*} = \gamma_b^{N^*}$. When the signal is $-\theta_0$, if $\gamma_b^{N^*} < {\gamma_m}^{N2^*}$, the final pledge rate is $\gamma^{N^*} = \gamma_b^{N^*}$ and the manufacturer cannot realize his optimal output.*

When observing θ_0, if $\gamma_b^{N^*} \geq {\gamma_m}^{N1^*}$, the pledge rate that can optimize the bank's profit is larger than that that can realize the manufacturer's optimal output. In this scenario, $\gamma_b^{N^*}$ has no binding force on the manufacturer. However, the manufacturer invests all its capital in operations and has no speculation, which means that it has no incentive to borrow more money. Hence, the bank should set the pledge rate based on $\gamma_m^{N1^*}$. In this case, the manufacturer's output is $q_m^{N1^*}$, and the emission abatement level is $\varepsilon_m^{N1^*}$. On the contrary, if $\gamma_b^{N^*} < {\gamma_m}^{N1^*}$, by setting the pledge rate based on $\gamma_b^{N^*}$, the bank can not only realize its optimal profit but also minimize non-performing assets caused by the manufacturer's bankruptcy risk. The determination of the pledge rate when observing an unfavorable signal $-\theta_0$ can be analyzed similarly.

Corollary 1. *$\gamma_b^{N^*}$ decreases with θ_0 and is immune to A_{H}.*

Corollary 1 shows that the optimal pledge rate highly depends on the signal value. As a large negative signal dramatically reduces market demand, the bank will offer a small pledge rate to control the loss caused by the manufacturer's bankruptcy. Contrary to our intuition, $\gamma_b^{N^*}$ is unrelated to A_{H}. In the high-demand state, the manufacturer does not face any bankruptcy risk. Thus, the bank can always recover the loan principal and interest regardless of how large $\gamma_b^{N^*}$ is. However, the bank needs to balance the profit and risk in a low-demand state because of the manufacturer's bankruptcy risk. Therefore, $\gamma_b^{N^*}$ is highly dependent on A_{L} and is immune to A_{H}.

In the no information sharing scenario, the supplier moves first as the Stackelberg game leader, and she infers the manufacturer's output and emission abatement level based on her prior belief to decide the wholesale price. According to the distributions of A and θ, four market demand cases can be established: taking $A_{\mathrm{H}} + \theta_0$ or $A_{\mathrm{H}} - \theta_0$ with possibility r/2 and taking $A_{\mathrm{L}} + \theta_0$ or $A_{\mathrm{L}} - \theta_0$ with possibility $(1-r)/2$. Denote q_s^K and $\varepsilon_s^K (K = N, \mathrm{PS}, \mathrm{PB}, S)$ as the output and carbon emission reduction inferred by the supplier, respectively. Then, the manufacturer's expected profit inferred by the supplier is written as

$$\begin{aligned} \pi_{ms}^N = & \frac{r}{2} \left(A_{\mathrm{H}} + \theta_0 - q_s^N + a\varepsilon_s^N \right) q_s^N + \frac{r}{2} \left(A_{\mathrm{H}} - \theta_0 - q_s^N + a\varepsilon_s^N \right) q_s^N \\ & + \frac{(1-r)}{2} \left(A_{\mathrm{L}} + \theta_0 - q_s^N + a\varepsilon \right) q_s^N - \frac{1+r}{2} \left(w^N q_s^N + \frac{\tau \varepsilon_s^{N2}}{2} - B \right) \\ & \times (1+R) - \frac{1+r}{2} p_c \left[e_0 \left(1 - \varepsilon_s^N \right) q_s^N - G \right] - B. \end{aligned} \tag{7}$$

Thus, the manufacturer's output and emission abatement level inferred by the supplier are $q_s^{N^*} = \frac{\tau(1+R)\left[(1-r)(A_{\mathrm{L}}-\theta_0-p_c e_0)+2rA_{\mathrm{H}}-w^N(1+r+rR+R)\right]}{(1+r)\left[2\tau(1+R)-(p_c e_0+a)^2\right]}$ and $\varepsilon_s^{N^*} = \frac{(p_c e_0+a)\left[(1-r)(A_{\mathrm{L}}-\theta_0-p_c e_0)+2rA_{\mathrm{H}}-w^N(1+r+rR+R)\right]}{(1+r)\left[2\tau(1+R)-(p_c e_0+a)^2\right]}$, respectively.

Then, in the no information sharing scenario, the supplier's expected profit is written as

$$\pi_s^N = \left(w^N - c\right) q_s^{N^*}. \tag{8}$$

From the above analysis, we can determine the supplier's optimal wholesale price decision in a no-information-sharing scenario.

Proposition 4. *In the no information sharing scenario, the optimal wholesale price offered by the manufacturer is* $w^{N^*} = \frac{(1-r)(A_{\mathrm{L}}+\theta_0)+2rA_{\mathrm{H}}-p_c e_0(1+r)+c(1+r)(1+R)}{2(1+r)(1+R)}$.

Evidently, the optimal wholesale price increases with market demand and the ordering cost per unit item, while it decreases with the carbon price, carbon emissions per unit product, and the interest rate. However, the relationship between w and the prior possibility of high demand r is inconclusive. When the gap between high and low demand is large, that is, $A_{\mathrm{H}} - A_{\mathrm{L}} > \theta_0$, the inherent randomness crucially affects the supplier's decision. With a higher probability of the high-demand state, the supplier sets a larger w. However, when the distance between the high- and low-demand states is relatively small, higher wholesale price may cause the manufacturer to remain inactive in terms of ordering materials. Therefore, the supplier needs to weaken the effect of market disturbance by setting a lower wholesale price to induce a higher order quantity.

3.3. Partially sharing information

3.3.1. Partially sharing information with the supplier

In this scenario, the supplier updates her belief in the market demand based on the information shared by the manufacturer. Given the wholesale price, when observing the signal θ_0, the manufacturer's expected profit is written as

$$\begin{aligned}\pi_m^{\mathrm{PS1}} &= r\left(A_{\mathrm{H}} + \theta_0 - q_m^{\mathrm{PS1}} + a\varepsilon_m^{\mathrm{PS1}}\right) q_m^{\mathrm{PS1}} + (1-r)\left(A_{\mathrm{L}} + \theta_0 - q_m^{\mathrm{PS1}} + a\varepsilon_m^{\mathrm{PS1}}\right) q_m^{\mathrm{PS1}} \\ &\quad - \left(w^{\mathrm{PS}} q_m^{\mathrm{PS1}} + \frac{\tau\left(\varepsilon_m^{\mathrm{PS1}}\right)^2}{2} - B\right)(1+R) - p_c\left[e_0\left(1-\varepsilon_m^{\mathrm{PS1}}\right) q_m^{\mathrm{PS1}} - G\right] - B.\end{aligned} \tag{9}$$

When observing $-\theta_0$, the manufacturer's expected profit is

$$\begin{aligned}\pi_m^{\mathrm{PS2}} = r\Bigg[&\left(A_{\mathrm{H}} - \theta_0 - q_m^{\mathrm{PS2}} + a\varepsilon_m^{\mathrm{PS2}}\right) q_m^{\mathrm{PS2}} - \left(w^{\mathrm{PS}} q_m^{\mathrm{PS2}} + \frac{\tau\left(\varepsilon_m^{\mathrm{PS2}}\right)^2}{2} - B\right)(1+R) \\ &- p_c\left(e_0\left(1-\varepsilon_m^{\mathrm{PS2}}\right) q_m^{\mathrm{PS2}} - G\right)\Bigg] - B.\end{aligned} \tag{10}$$

The bank still makes decisions based on the prior belief about market demand, which is the same as the no information sharing setting in Section 3.1. The expected profit of the supplier is given by

$$\pi_s^{\mathrm{PS}} = \left(w^{\mathrm{PS}} - c\right) q_m^{\mathrm{PS}}. \tag{11}$$

Then, we can present Proposition 5 that characterizes the optimal decision of every party when partially sharing information with the supplier.

Proposition 5. (a) *When sharing a signal* $\theta_0, w^{\mathrm{PS1}^*} = \frac{u+\theta_0-p_c e_0+c(1+R)}{2(1+R)}, \gamma^{\mathrm{PS1}^*} = \min\left[\gamma_b^{N^*}, {\gamma_m}^{\mathrm{PS1}^*}\right], q_m^{\mathrm{PS1}^*} = \frac{\tau(1+R)(u+\theta_0-c-cR-p_c e_0)}{4\tau(1+R)-2(p_c e_0+a)^2}$, *and* $\varepsilon_m^{\mathrm{PS1}^*} = \frac{(p_c e_0+a)(u+\theta_0-c-cR-p_c e_0)}{4\tau(1+R)-2(p_c e_0+a)^2}$.

(b) *When sharing a signal* $-\theta_0, w^{\mathrm{PS2}^*} = \frac{r(A_{\mathrm{H}}-\theta_0-c-cR)-p_c e_0}{2r(1+R)}, \gamma^{\mathrm{PS2}^*} = \min\left[\gamma_b^{N^*}, {\gamma_m}^{\mathrm{PS2}^*}\right]$, $q_m^{\mathrm{PS2}^*} = \frac{\tau r(1+R)(r(A_{\mathrm{H}}+\theta_0-c-cR)-p_c e_0)}{4r^2\tau(1+R)-2(p_c e_0+ar)^2}$, *and* $\varepsilon_m^{\mathrm{PS2}^*} = \frac{(p_c e_0+ar)(r(A_{\mathrm{H}}+\theta_0-c-cR)-p_c e_0)}{4\tau r^2(1+R)-2(p_c e_0+ar)^2}$.

Proposition 5 demonstrates that when sharing a favorable signal, the equilibrium wholesale price is closely related to the market potential in high- and low-demand states, whereas it solely depends on the high market potential if the supplier obtains negative demand information. In contrast to the scenario with no information sharing, the results show that the optimal wholesale price increases with the prior belief in the high-demand state in the partial information sharing scenario. This implies that participants respond positively when the likelihood of a high-demand state is large. The bank compares the minimum pledge rate that guarantees the manufacturer's optimal decision with the optimal pledge rate that maximizes its profit, and then chooses the smaller one.

3.3.2. Partially sharing information with the bank

If the manufacturer conveys information solely to the bank, the supplier makes a decision based on the prior belief about market demand. Then, the wholesale price is the same as that described in Section 3.1, *i.e.*, $w^{\mathrm{PB}^*} = w^{N^*}$. As a result, when the signal is θ_0, $q_m^{\mathrm{PB1}^*} = q_m^{N1^*}$ and $\varepsilon_m^{\mathrm{PB1}^*} = \varepsilon_m^{N1^*}$. The minimized pledge rate that ensures that the manufacturer achieves optimal output satisfies the equation $\gamma_m^{\mathrm{PB1}^*} p_c V = w^{\mathrm{PB}^*} q_m^{\mathrm{PB1}^*} + \frac{\tau(\varepsilon_m^{\mathrm{PB1}^*})^2}{2} - B$. Thus, the final pledge rate is set on $\gamma^{\mathrm{PB1}^*} = \gamma_m^{\mathrm{PB1}^*} = \gamma_m^{N1^*}$, as the manufacturer faces no bankruptcy risk.

Similarly, we obtain the manufacturer's optimal decisions $q_m^{\mathrm{PB2}^*} = q_m^{N2^*}$ and $\varepsilon_m^{\mathrm{PB2}^*} = \varepsilon_m^{N2^*}$ when sharing $-\theta_0$. The minimized pledge rate required by the manufacturer to achieve optimal output is $\gamma_m^{\mathrm{PB2}^*} = \gamma_m^{N2^*}$. In this scenario, the bank chooses the pledge rate by maximizing its expected profit

$$\begin{aligned}\pi_b^{\mathrm{PB2}} &= (1-r)\left[\left(A_{\mathrm{L}} - \theta_0 - q_b^{\mathrm{PB2}} + a\varepsilon_b^{\mathrm{PB2}}\right) q_b^{\mathrm{PB2}} - p_c\left(e_0\left(1-\varepsilon_b^{\mathrm{PB2}}\right) q_b^{\mathrm{PB2}} - G\right)\right] \\ &\quad + (1+r)\left(w^{\mathrm{PB}} q_b^{\mathrm{PB2}} + \frac{\tau\varepsilon_b^{\mathrm{PS2}}}{2} - B\right)(1+R) - \left(w^{\mathrm{PB}} q_b^{\mathrm{PB2}} + \frac{\tau\varepsilon_b^{\mathrm{PB2}}}{2} - B\right).\end{aligned} \tag{12}$$

Then, we can get

$$q_b^{\mathrm{PB2}^*} = \frac{\tau(1-r-rR)\left[(1-r)\left(A_{\mathrm{L}} - \theta_0 - p_c e_0\right) - w^{\mathrm{PB}^*}(1-r-rR)\right]}{(1-r)\left[2\tau(1-r-rR) - (1-r)\left(p_c e_0 + a\right)^2\right]} \tag{13}$$

$$\varepsilon_b^{\mathrm{PB2}^*} = \frac{\left(p_c e_0 + a\right)\left[(1-r)\left(A_{\mathrm{L}} - \theta_0 - p_c e_0\right) - w^{\mathrm{PB}^*}(1-r-rR)\right]}{2\tau(1-r-rR) - (1-r)\left(p_c e_0 + a\right)^2}. \tag{14}$$

The pledge rate $\gamma_b^{\mathrm{PB2}^*}$ also satisfies $\gamma_b^{\mathrm{PB2}^*} p_c V = w^{\mathrm{PB}^*} q_b^{\mathrm{PB2}^*} + \frac{\tau(\varepsilon_b^{\mathrm{PB2}^*})^2}{2} - B$. Similar to the case in the no information sharing scenario, the final pledge rate is decided by $\min[\gamma_b^{\mathrm{PB2}^*}, \gamma_m^{\mathrm{PB2}^*}]$; $\gamma_m^{\mathrm{PB2}^*}$ satisfies the equation $\gamma_m^{\mathrm{PB2}^*} p_c V = w^{\mathrm{PB}^*} q_m^{\mathrm{PB2}^*} + \frac{\tau(\varepsilon_m^{\mathrm{PB2}^*})^2}{2} - B$. Hence, we obtain the next proposition that depicts the bank's optimal decision.

Proposition 6. *When observing* $\theta_0, \gamma^{\mathrm{PB1}^*} = \gamma_m^{\mathrm{PB1}^*}$*; when observing* $-\theta_0$*,* $\gamma^{\mathrm{PB2}^*} = \min\left[\gamma_m^{\mathrm{PB2}^*}, \gamma_b^{\mathrm{PB2}^*}\right]$.

From Proposition 6, we know that compared with the no information sharing scenario, the manufacturer can realize his optimal decision by sharing a favorable signal θ_0 with the bank. Additionally, sharing information helps the bank reduce unfavorable assets, resulting in a deterministic pledge rate, *i.e.*, $\gamma_b^{\mathrm{PS1}^*} = \gamma_m^{\mathrm{PS1}^*}$. When sharing an unfavorable signal, the final pledge rate is uncertain, and the manufacturer may not realize his optimal output in the bankruptcy scenario.

3.4. Public information sharing

This section analyzes the setting in which the manufacturer publicly shares his private demand information. When the manufacturer shares information with all members, the expressions of output and carbon emission reduction remain the same as when partially sharing information with the supplier, *i.e.*, $q_m^{S^*} = q_m^{\mathrm{PS}^*}$ and $\varepsilon_m^{S^*} = \varepsilon_m^{\mathrm{PS}^*}$. The bank and supplier make decisions based on the shared information.

When the signal is θ_0. The bank can recover the entire loan principal and interest. Then, its expected profit is

$$\pi_b^{S1} = \left(w^{S1} q_m^{S1} + \frac{\tau \varepsilon_m^{S12}}{2} - B \right) R. \tag{15}$$

The optimal pledge rate satisfies $\gamma_m^{S1^*} V p_c = w^{S1} q_m^{S1} + \frac{1}{2} \tau \varepsilon_m^{S1^2} - B$.

When observing $-\theta_0$, the manufacturer faces a bankruptcy risk in a low-demand state. The bank's revenue takes $(w^{S2} q_m^{S2} + \frac{\tau \varepsilon_m^{S22}}{2} - B)(1+R)$ with the possibility r and $(A_{\mathrm{L}} - \theta_0 - q_m^{S2} + a\varepsilon_m^{S2}) q_m^{S2} - p_c(e_0(1 - \varepsilon_m^{S22}) q_m^{S2} - G)$ with possibility $(1-r)$. Thus, the bank's expected profit can be written as

$$\begin{aligned} \pi_b^{S2} = {} & (1-r) \left[\left(A_{\mathrm{L}} - \theta_0 - q_b^{S2} + a \varepsilon_b^{S2} \right) q_b^{S2} - p_c \left(e_0 \left(1 - \varepsilon_b^{S2} \right) q_b^{S2} - G \right) \right] \\ & + r \left(w^{S2} q_b^{S2} + \frac{\tau \varepsilon_b^{S22}}{2} - B \right) (1+R) - \left(w^{S2} q_b^{S2} + \frac{\tau \varepsilon_b^{S22}}{2} - B \right). \end{aligned} \tag{16}$$

We can get

$$q_b^{S2^*} = \frac{\tau (1 - r - rR) \left[(1-r) \left(A_{\mathrm{L}} - \theta_0 - p_c e_0 \right) - w^{S2} (1 - r - rR) \right]}{(1-r) \left[2\tau (1 - r - rR) - (1-r) \left(p_c e_0 + a \right)^2 \right]} \tag{17}$$

$$\varepsilon_b^{S2^*} = \frac{\left(p_c e_0 + a \right) \left[(1-r) \left(A_{\mathrm{L}} - \theta_0 - p_c e_0 \right) - w^{S2} (1 - r - rR) \right]}{2\tau (1 - r - rR) - (1-r) \left(p_c e_0 + a \right)^2}. \tag{18}$$

Then, the bank optimizes its expected profit by choosing a pledge rate $\gamma_b^{S2^*}$ that satisfies $\gamma_b^{S2^*} p_c V = w^{S2} q_b^{S2^*} + \frac{\tau \varepsilon_b^{S2^* 2}}{2} - B$.

The supplier maximizes her expected profit $\pi_s^{S1} = (w^{S1} - c) q_m^{S1}$ by deciding w^{S1} when sharing positive demand information and maximizing $\pi_s^{S2} = (w^{S2} - c) q_m^{S2}$ by choosing w^{S2} when sharing negative demand information. The following proposition describes each participant's optimal decision in a public information sharing setting.

Proposition 7. (a) *When sharing a signal* $\theta_0, w^{S1^*} = \frac{u + \theta_0 - p_c e_0 + c(1+R)}{2(1+R)}, \gamma^{S1^*} = \gamma_m^{S1^*}, q_m^{S1^*} = \frac{\tau (1+R)(u + \theta_0 - c - cR - p_c e_0)}{4\tau (1+R) - 2(p_c e_0 + a)^2}$, *and* $\varepsilon_m^{S1^*} = \frac{(p_c e_0 + a)(u + \theta_0 - c - cR - p_c e_0)}{4\tau (1+R) - 2(p_c e_0 + a)^2}$.

(b) *When sharing a signal* $-\theta_0, w^{S2^*} = \frac{r(A_{\mathrm{H}} - \theta_0 - c - cR) - p_c e_0}{2r(1+R)}, \gamma^{S2^*} = \min[\gamma_m^{S2^*}, \gamma_b^{S2^*}], q_m^{S2^*} = \frac{\tau r (1+R)(r(A_{\mathrm{H}} + \theta_0 - c - cR) - p_c e_0)}{4r^2 \tau (1+R) - 2(p_c e_0 + ar)^2}$ *and* $\varepsilon_m^{S2^*} = \frac{(p_c e_0 + ar)(r(A_{\mathrm{H}} + \theta_0 - c - cR) - p_c e_0)}{4\tau r^2 (1+R) - 2(p_c e_0 + ar)^2}$.

Comprehensively considering Propositions 5–7, we find that the supplier's decision highly relies on the manufacturer's order quantity and has nothing to do with the pledge rate, whereas the bank's decision depends on the wholesale price and the manufacturer's decision. Recalling the optimal decision when sharing information with the bank in Section 3.2, we also find that the pledge rate is fixed when the bank receives positive demand information. In this context, the bank acts as a pledge rate taker rather than a pledge rate maker. When the bank receives negative demand information, it plays the role of a pledge-rate maker if the loan size of the manufacturer is relatively large. In this case, the manufacturer may not achieve the best output and carbon emission reduction level if the negative signal is relatively large.

4. Impacts of information sharing

Thus far, we have analyzed each participant's decisions under three different information-sharing formats. However, we still do not know how different informationsharing formats affect each member. In this section, we analyze the impacts of information sharing on optimal decisions and profits. Regarding the impact of information sharing on optimal decisions, the following proposition holds.

Proposition 8. (a) *When observing a favorable signal,* ${w}^{N^*} > {w}^{\mathrm{PS1}^*} = {w}^{S1^*}$, ${q_m}^{N1^*} < {q_m}^{\mathrm{PS1}^*} = {q_m}^{S1^*}$, *and* ${\varepsilon_m}^{N1^*} < {\varepsilon_m}^{\mathrm{PS1}^*} = {\varepsilon_m}^{S1^*}$ *if* $\theta_0 < \frac{A_{\mathrm{H}}-A_{\mathrm{L}}}{2(1-r)}$; ${w}^{N^*} = {w}^{\mathrm{PB1}^*} > {w}^{S1^*}$, ${q_m}^{N1^*} = {q_m}^{\mathrm{PB1}^*} < {q_m}^{S1^*}$, *and* ${\varepsilon_m}^{N1^*} = {\varepsilon_m}^{\mathrm{PB1}^*} < {\varepsilon_m}^{S1^*}$ *if* $\theta_0 < \frac{A_{\mathrm{H}}-A_{\mathrm{L}}}{2(1-r)}$; *the relationship among the pledge rates is inconclusive.*

(b) *When observing an unfavorable signal,* $w^{S2^*} = w^{\mathrm{PS2}^*} > w^{N^*}, q_m^{S2^*} = q_m^{\mathrm{PS2}^*} < q_m^{N2^*}$, *and* $\varepsilon_m^{S2^*} = \varepsilon_m^{\mathrm{PS2}^*} < \varepsilon_m^{N2^*}$ *if* $\theta_0 > \frac{-p_c e_0(1-r^2)+(r-r^2)(A_{\mathrm{H}}-A_{\mathrm{L}})}{2r}$; $w^{S2^*} > w^{\mathrm{PB2}^*} = w^{N^*}, q_m^{S2^*} < q_m^{\mathrm{PB2}^*} = q_m^{N2^*}$, *and* $\varepsilon_m^{S2^*} < \varepsilon_m^{\mathrm{PB2}^*} = \varepsilon_m^{N2^*}$ *if* $\theta_0 > \frac{-p_c e_0(1-r^2)+(r-r^2)(A_{\mathrm{H}}-A_{\mathrm{L}})}{2r}$; *the relationship among the pledge rates is inconclusive.*

Proposition 8 shows that the impacts of information sharing on optimal decisions depend on the sharing format. It shows that the supplier's and manufacturer's optimal decisions are the same as those in the no-information-sharing and partial-information-sharing scenarios. However, this may not be the manufacturer's final decision because the pledge rate may change in different settings. If positive demand information is shared publicly, the supplier's decision mainly hinges on the inherent uncertainty of the market and the disturbance. Interestingly, the supplier does not always respond positively to favorable signals. When the disturbance is smaller than a certain value, the wholesale price in the no information sharing scenario is larger than that in the public information sharing scenario. In the no information sharing case, the optimal output and emission abatement level inferred by the supplier are overrated because of the manufacturer's limited repayment liability. When sharing a positive signal, the supplier, on the one hand, adjusts her belief in the manufacturer's decision to the unbiased state; on the other hand, she responds positively to the favorable signal. If the former effect dominates the latter, then the wholesale price in public information sharing is smaller. Otherwise, $w^{S1^*} > w^{\mathrm{PB1}^*} = w^{N^*}$ holds. The changes in optimal output and emission abatement are opposite because of the negative relationship between them and the wholesale price. This implies that publicly sharing favorable signals does not always decrease the manufacturer's output or carbon emission abatement level. The case in which an unfavorable signal is publicly shared can be analyzed in a similar manner. The pledge rate is affected by both the wholesale price and the manufacturer's decision. Thus, the impact of public information sharing on the pledge rate is uncertain. However, we can establish a feature of the pledge rate.

Corollary 2. *When the bank receives* θ_0*, the pledge rate is deterministic. When it receives* $-\theta_0$*, the pledge rate is no larger than that in the no-information-sharing scenario.*

The results are primarily influenced by the bankruptcy risk faced by the manufacturer in the various scenarios. When observing θ_0, the manufacturer does not confront any bankruptcy risk, and the final pledge rate is set based on $\gamma_m^{K1^*}$. However, when observing an unfavorable signal, the bank considers the probability of the manufacturer's bankruptcy; hence, the pledge rate changes with bankruptcy risk. The relationship among pledge rates in different settings is analyzed using numerical examples. The result also indicates that when sharing a favorable signal, the manufacturer can make optimal decisions; however, unfavorable signal transmission complicates their final decision.

The next proposition describes the impacts of information sharing on each member's profit.

Proposition 9. (a) *When observing the signal* $\theta_0, \pi_m^{S1^*} = \pi_m^{\mathrm{PS1}^*} \geq \pi_m^{N1^*}$ *and* $\pi_m^{S1^*} \geq \pi_m^{\mathrm{PB1}^*} = \pi_m^{N1^*}$ *if* $\theta_0 \leq \frac{A_{\mathrm{H}}-A_{\mathrm{L}}}{2(1-r)}; \pi_s^{S1^*} = \pi_s^{\mathrm{PS1}^*} \geq \pi_s^{N1^*}$ *and* $\pi_s^{S1^*} \geq \pi_s^{\mathrm{PB1}^*} = \pi_s^{N1^*}$.

(b) *When observing the signal* $-\theta_0, \pi_m^{S2^*} = \pi_m^{\mathrm{PS2}^*} \geq \pi_m^{N2^*}$ *and* $\pi_m^{S2^*} \geq \pi_m^{\mathrm{PB2}^*} = \pi_m^{N2^*}$ *if* $\theta_0 \leq \frac{r[A_{\mathrm{H}}(3+r)-A_{\mathrm{L}}(1-r)-2c(1+r)(1+R)]-(1+r)p_c e_0}{2r(2+r)}; \pi_s^{S2^*} = \pi_s^{\mathrm{PS2}^*} \geq \pi_s^{N2^*}$ *and* $\pi_s^{S2^*} \geq \pi_s^{\mathrm{PB2}^*} = \pi_s^{N2^*}$ *if* $\theta_0 \leq \frac{A_{\mathrm{H}}-A_{\mathrm{L}}}{2(1-r)}$.

Proposition 9(a) demonstrates that if the supplier is informed of positive demand information, she always benefits from information sharing. For the manufacturer, he benefits from public information sharing if the signal value is smaller than a certain value. When the signal is relatively large, *i.e.*, $\theta_0 > \frac{A_{\mathrm{H}}-A_{\mathrm{L}}}{2(1-r)}$, a much higher wholesale price reduces the manufacturer's order quantity, resulting in lower output and lower emission abatement level. In this scenario, both the effects of a higher wholesale price and a lower marginal profit hurt the

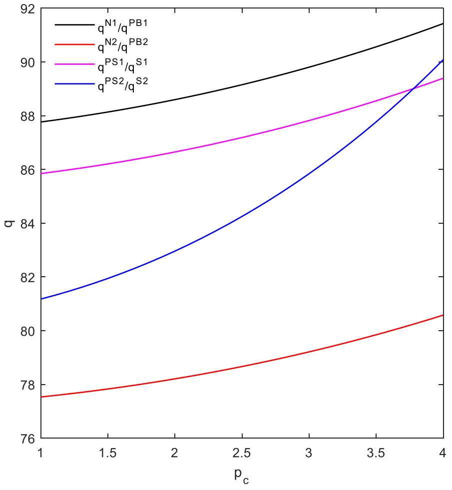

FIGURE 2. Impact of p_c on q.

manufacturer compared to the case in which no information is shared. Proposition 9(b) reveals that when the signal value is not large, the manufacturer benefits from partially sharing negative information with the supplier or pubic information sharing. Interestingly, there is a scenario in which the supplier also benefits from sharing negative information. With a small θ_0, the wholesale price responds to the unfavorable signal weakly. In this scenario, the emission abatement level increases gradually, prompting the manufacturer to increase production quantity in response to consumers' growing environmental awareness. When the positive output effect is larger than the negative wholesale price effect, the supplier makes a profit from negative information sharing.

Additionally, Proposition 9 offers managerial insights for manufacturers to effectively manage market demand information. When the demand gap is not large, the manufacturer should consider public information sharing or partial information sharing with the supplier; otherwise, it is best for them not to share information at all or to share it only with the bank. Proposition 9 also indicates that supply chain members benefit from public information sharing when $\theta_0 \leq \min[\frac{r[A_{\mathrm{H}}(3+r)-A_{\mathrm{L}}(1-r)-2c(1+r)(1+R)]-(1+r)p_c e_0}{2r(2+r)}, \frac{A_{\mathrm{H}}-A_{\mathrm{L}}}{2(1-r)}]$, regardless of whether they share favorable or unfavorable signals. This means that publicly sharing information helps improve supply chain performance. As the expression of bank profit is highly complicated, we will discuss the impact of information sharing on the bank in numerical experiment section.

5. NUMERICAL EXPERIMENT

To duly illustrate the results obtained from the above-stated analysis and explore insights that are challenging to obtain from the analytical results, we conduct numerical experiments in this section. Referring to the related literature [10,26,31,38], we try several sets of parameter values to perform the numerical experiment. The results presented thereby are similar. Here, the parameters are set as follows: $A_{\mathrm{H}} = 400, A_{\mathrm{L}} = 200, c = 30, R = 0.08, e_0 = 2, \tau = 1000, a = 5, G = 2000, V = 1500, r = 0.6$, and $B = 10\,000$. All the aforementioned parameters satisfy the model assumptions.

The first set of numerical experiments examines the impact of carbon trading price p_c. In this setting, the signal value is fixed, *i.e.*, $\theta_0 = 50$. Figure 2. shows that the optimal output increases with p_c. This is because the value of mortgaged carbon assets is high owing to the high carbon price. In this case, the manufacturer can obtain more loans to invest in production. When the carbon price is high, the manufacturer can save more carbon emission permits for pledging or trading in the carbon market by improving its carbon emission reduction level. Hence, ε increases with p_c, as shown in Figure 3. Interestingly, the wholesale price decreases with p_c owing

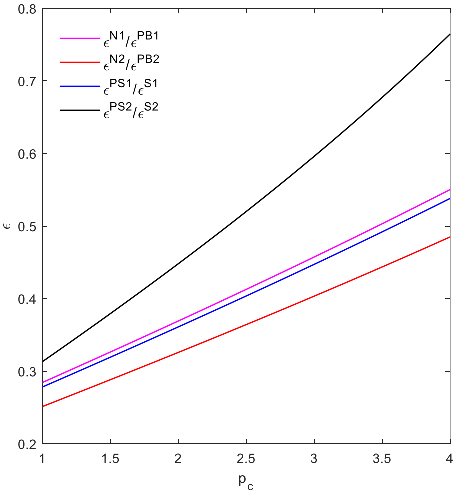

Figure 3. Impact of p_c on ε.

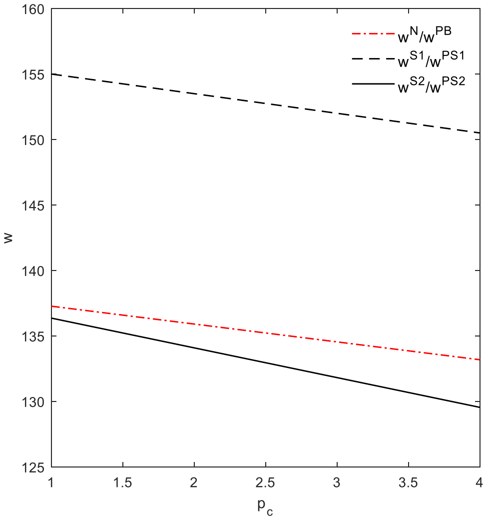

Figure 4. Impact of p_c on w.

to the negative correlation between w and q, as shown in Figure 4. The higher the carbon trading price at the beginning of the period, the greater the possibility of the depreciation of the carbon assets at the end. Thus, the bank tends to lower the pledge rate to avoid the loss caused by the devaluation of carbon assets, as depicted in Figure 5, wherefrom we can also see that the pledge rate in the no information sharing scenario is larger than that when negative information is publicly shared, whereas it is smaller than that in the positive information sharing scenario. The intuition behind this result is that the bank recovers all the loan principal and interest when obtaining a positive signal. In this setting, the bank offers a higher pledge rate to the manufacturer to make more profits.

Both effects of carbon emission permits, being pledged to obtain a loan to invest in production and being traded in the carbon market to get revenue, generate profits for the manufacturer. Therefore, π_m^N increases with

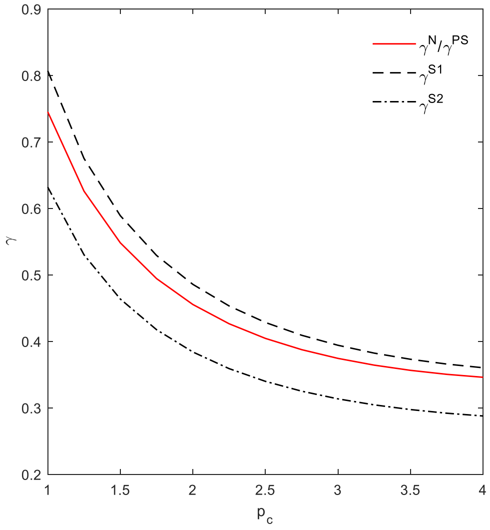

FIGURE 5. Impact of p_c on γ.

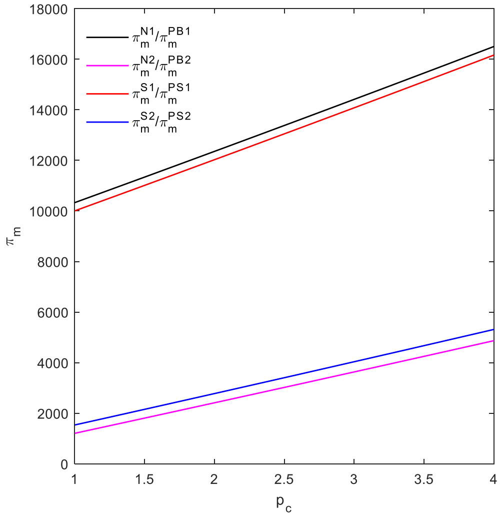

FIGURE 6. Impact of p_c on π_m^N.

p_c. Figure 6 also shows that the favorable disturbance signal increases the manufacturer's profit due to the increased market demand. The above analysis shows that the manufacturer's output and emission abatement level increase with p_c. The supplier can benefit from the increased carbon price provided that the positive effect of the output exceeds the negative effect of the wholesale price. Given the initial capital, the manufacturer needs more due to the increased output and emission abatement level. Hence, the bank's profit is also positively correlated with p_c, as shown in Figure 7.

Figure 8 shows that the final pledge rate is set based on $\gamma_m^{N1^*}$ when the signal value is relatively small in the no information sharing scenario, and it is equal to $\gamma_b^{N^*}$ when the signal value is large. This implies that when the real disturbance signal is positive, the manufacturer's output and emission abatement are overrated by the bank in the no information sharing scenario. We can also see that the pledge rates in information sharing scenarios

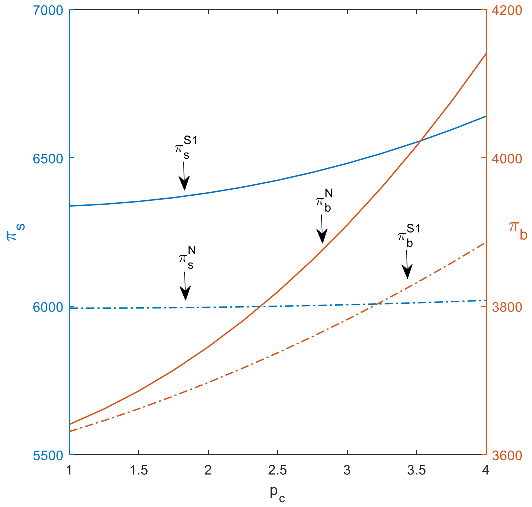

FIGURE 7. Impact of p_c on π_s^N and π_b^N.

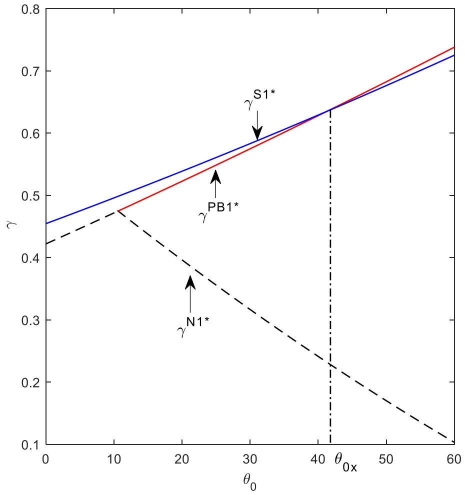

FIGURE 8. Impact of positive information on γ.

are larger than that in the no information sharing scenario due to the bank's positive response to the signal. Compared to partial information sharing, the pledge rate in the public information sharing scenario is smaller if the disturbance signal is large, that is, $\theta_0 > \theta_{0x}$. In contrast, there exists $\gamma^{N^*} \geq \gamma^{\mathrm{PB2}^*} > \gamma^{S2^*}$ when $\theta_0 < \theta_{0y}$, as shown in Figure 9. This is because sharing a negative signal enhances the expectation of the bankruptcy possibility of the manufacturer. However, the supplier cuts the wholesale price dramatically when she gains a rather pessimistic signal about the market. In this case, the manufacturer's order quantity increases, facilitating the final output. Therefore, the bank is willing to provide a higher pledge rate. Thus, $\gamma^{S2^*} > \gamma^{N^*} \geq \gamma^{\mathrm{PB2}^*}$ when $\theta_0 > \theta_{0y}$.

This set of numerical studies tries to investigate the effect of public information sharing on each party's profit. Figures 10 and 11 show that information sharing benefits the manufacturer when θ_0 is relatively small. Contrary to our intuition, the findings show that banks benefit (suffer) from negative (positive) information sharing. When

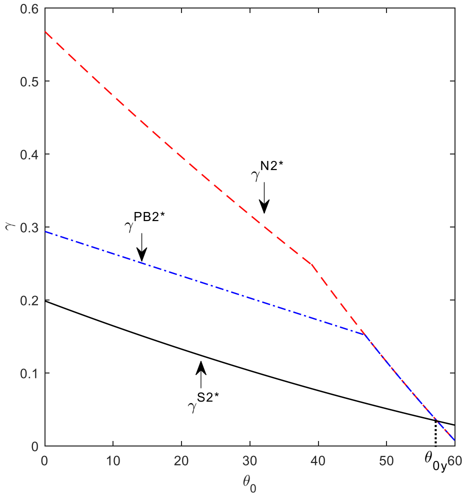

FIGURE 9. Impact of negative information on γ.

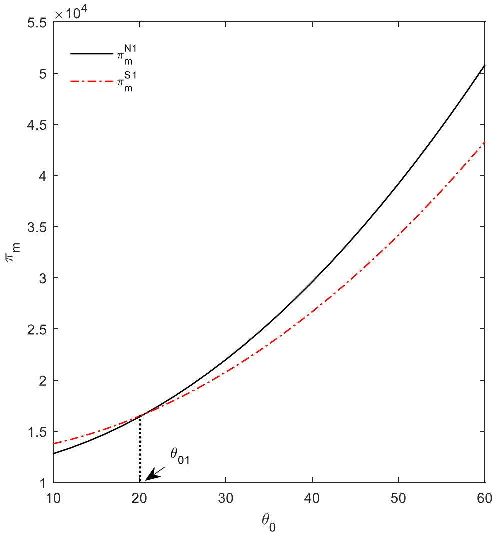

FIGURE 10. Impact of positive information on π_m.

the bank receives positive information, it means that the manufacturer's output is in the no bankruptcy region. In this scenario, the pledge rate offered by the bank is no larger than that in the no information sharing setting, and a lower profit is always accompanied by a lower risk, as reflected in Figure 12. Figure 13 shows that the supplier can benefit from negative information sharing when $\theta_0 < \theta_{03}$, whereas she always benefits from positive information sharing. The numerical study indicates that a region exists wherein public information sharing, regardless of whether it is positive or negative information, benefits the supplier and manufacturer. However, the bank benefits from information sharing only when it obtains an unfavorable signal.

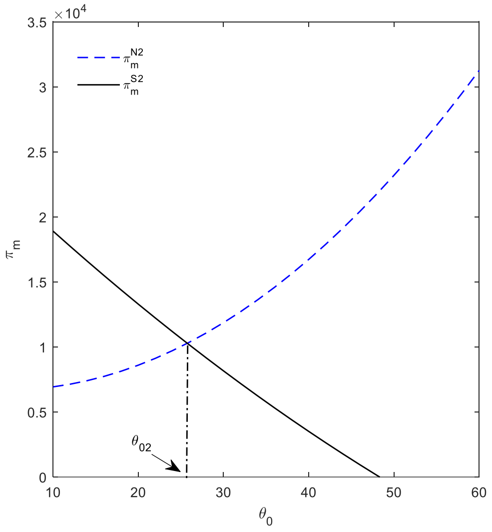

FIGURE 11. Impact of negative information on π_m.

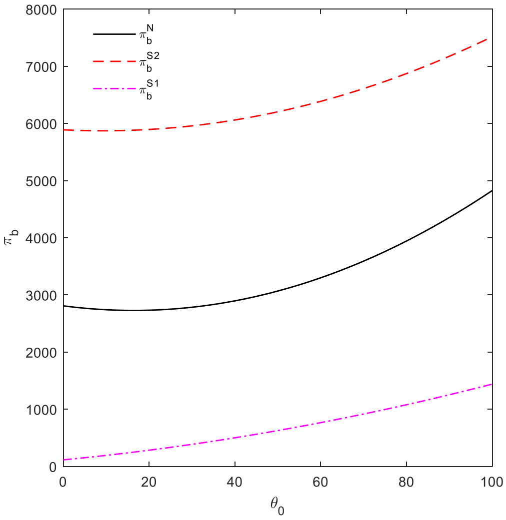

FIGURE 12. Impact of θ on π_b.

6. MANAGERIAL IMPLICATIONS

Based on this study, several meaningful managerial implications can be drawn. First, the manufacturer should fully consider the information on the demand and carbon market to determine the optimal output and carbon emission reduction level. The paper reveals that the carbon emission reduction level and production quantity are affected by factors such as potential market demand, consumers' low-carbon preference, and carbon trading price. Therefore, the manufacturer should combine the information from both markets to make optimal decisions. For example, when the carbon trading price is high and consumers prefer green products, the manufacturer should increase its investment in carbon emission reduction. When market demand information is rather pessimistic, the manufacturer should reduce its production volume. Second, the manufacturer should strategically share

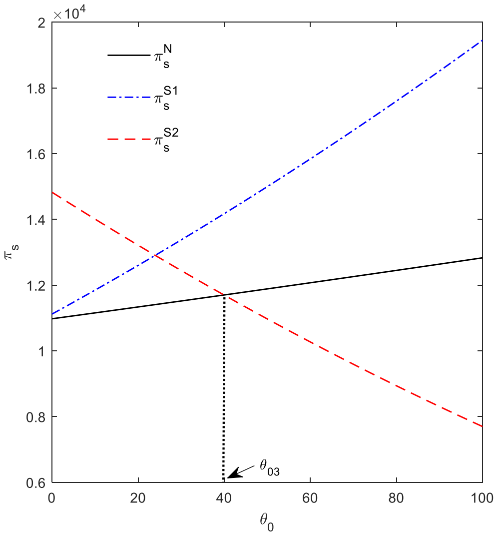

FIGURE 13. Impact of θ on π_s.

information with the bank. This study indicates that the ability of the manufacturer to make optimal decisions is also closely related to the pledge rate specified by the bank. Partially sharing positive information with the bank can encourage the latter to offer a stable pledge rate, thereby ensuring the achievement of the optimal output and carbon emission reduction. Therefore, the manufacturer can regularly provide screened and positive business data and operational indicators to the bank to enhance its confidence.

Third, the supplier should determine the optimal wholesale price based on the type of information shared by the manufacturer. This study indicates that when the manufacturer conveys optimistic signals, the wholesale price is associated with the disparity between highand low-demand levels. When the manufacturer shares a negative signal, the wholesale price is solely correlated with high-demand potential. Consequently, in the presence of optimistic information, the supplier can moderately lower the wholesale price to encourage the manufacturer to order more raw materials. For instance, the supplier can offer price discounts to the manufacturer. Conversely, when confronted with pessimistic information, the supplier ought to raise its wholesale price moderately to ensure profit.

Fourth, the bank must enhance its ability to screen the information shared by manufacturers. The findings show that when the manufacturer shares optimistic information, the bank sets a relatively high pledge rate. When sharing pessimistic demand information, the bank lowers the pledge rate. However, to obtain a higher pledge rate, the manufacturer may only convey some positive information. Therefore, the bank should strengthen its communication with manufacturers to verify whether the information provided by them is true and complete. For manufacturers that engage in unethical behaviors, including concealment and falsification, during the information sharing process, the bank can take punitive measures, such as lowering their credit ratings and restricting their loan limits.

Fifth, the manufacturer needs to accurately grasp changes in market demand to select an appropriate information sharing format. For instance, the manufacturer can use market research and data analysis to forecast market demand fluctuations. If the market demand fluctuation is small, the manufacturer can choose to share information publicly. If market demand fluctuates significantly, the manufacturer can choose to share information partially with the supplier. Moreover, the research shows that information sharing can also benefit the supplier; therefore, the supplier should take measures to induce the manufacturer to share information. For example, the supplier can establish an information sharing mechanism with the manufacturer and proactively divulge some of its information, such as inventory levels and production capacity expansion plans, to the manufacturer.

7. CONCLUSIONS

This study investigates the optimal decisions and impacts of information sharing in a supply chain with a capital-constrained manufacturer that borrows from a bank by pledging carbon emission permits under the carbon cap-and-trade regulation. Herein, we assume that the capital-constrained manufacturer has private information about market demand and decides on the information sharing format. Regulated by the cap-and-trade framework, the manufacturer decides on the output and invests in carbon emission reduction. Several interesting conclusions emerge from this study. The result reveals that both the optimal output and carbon emissions abatement are higher than those in the no bankruptcy scenario when the manufacturer faces bankruptcy risk and the signal value is relatively small. It also shows that partially sharing positive information with the bank guarantees that the manufacturer achieves optimal output and carbon emission reduction by inducing the bank to offer a constant pledge rate; however, signaling negative information to the bank may lower the output and emission abatement level. Interestingly, we find that sharing positive information with the supplier does not always lead to a higher wholesale price. The supplier may lower the wholesale price to induce a higher order quantity from the manufacturer. The type of information sharing format adopted by the manufacturer depends on prior belief with regard to market demand and the demand gap. If both the prior belief and the demand gap are small, the manufacturer chooses to partially share information with the supplier or share information publicly; otherwise, he chooses to partially share information with the bank or not share information at all. Regarding the impact of information sharing on firms' profits, we find that partially sharing positive information with the bank benefits each member, whereas sharing negative information with the bank is detrimental to them. Jointly considering the manufacturer's adjustment upon the expectation of the yield and emission abatement and the bank's response with regard to the pledge rate, there is a case in which public information sharing benefits the manufacturer and the supplier, regardless of whether sharing positive or negative information. Contrary to our intuition, the bank suffers when publicly sharing positive information because of the decreased pledge rate; however, it benefits from sharing negative information because of the lowered bankruptcy risk.

Although this study adds value to green supply chain financing and information sharing, it still has some limitations. First, this work assumes that the supplier is not concerned about carbon emission regulations. In practice, suppliers are also required by governments and even manufacturers to control carbon emissions. For instance, Apple has established a supplier audit mechanism that requires all its suppliers to comply with carbon emission standards. Second, this paper assumes that the manufacturer solely invests in carbon emission reduction. In some industries, the manufacturers, such as Lenovo Group Ltd. and Guangqi Honda Automobile Co. Ltd., cooperate with their upstream firms to reduce carbon emissions. Third, this work postulates that both the supplier and manufacturer are monopolists in the market. In fact, there is a certain degree of competition in any product market, and supply chain competition is a common form. Furthermore, competitors may also cooperate with each other in some aspects. For example, Toyota and General Motors collaborated in the research and development of environmentally friendly vehicles such as low-pollution gasoline engine vehicles and new types of low-pollution fuel vehicles.

Considering the limitations of this study, there are several potential research directions for future exploration. First, future research can consider both the supplier and manufacturer under carbon emission regulations. For example, both the supplier and manufacturer invest in carbon emission reduction, and they have different efficiencies in reducing carbon emissions. Second, assuming that the supplier and manufacturer cooperate to reduce carbon emissions, future studies can explore the most beneficial cooperation mode for both parties with asymmetric information, and this includes cost sharing, technology sharing, and patent licensing. Third, it would be interesting to investigate the competing settings among upstream or downstream firms and the scenarios whereby supply chains compete in the market. For example, future study can investigate how information sharing affects green supply chain financing when two supply chains compete with each other in the market.

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Data availability statement

The research data associated with this article are included in the article.

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APPENDIX A.

Proof of Proposition 1. From equation (1), taking the first and second derivatives of π_m^{N1} with respect to q_m^{N1} and ε_m^{N1}, we get

$$\begin{aligned}
\frac{\partial \pi_m^{N1}}{\partial q_m^{N1}} &= r\left(A_{\mathrm{H}} - 2q_m^{N1} - w^N - w^N R + a\varepsilon_m^{N1} + \theta_0\right) - p_c e_0\left(1 - \varepsilon_m^{N1}\right) \\
&\quad + (1-r)\left(A_{\mathrm{H}} - 2q_m^{N1} - w^N - w^N R + a\varepsilon_m^{N1} + \theta_0\right) && \text{(A.1)} \\
\frac{\partial^2 \pi_m^{N1}}{\partial q_m^{N12}} &= -2 && \text{(A.2)} \\
\frac{\partial \pi_m^{N1}}{\partial \varepsilon_m^{N1}} &= a q_m^{N1} + p_c e_0 q_m^{N1} - (1+R)\tau\varepsilon_m^{N1} && \text{(A.3)} \\
\frac{\partial^2 \pi_m^{N1}}{\partial \varepsilon_m^{N12}} &= -(1+R)\tau && \text{(A.4)} \\
\frac{\partial^2 \pi_m^{N1}}{\partial \varepsilon_m^{N1}\partial q_m^{N1}} &= a + p_c e_0. && \text{(A.5)}
\end{aligned}$$

Based on equations (A.2), (A.4), and (A.5), Hessian Matrix is given by

$$H\left(q_m^{N1}, \varepsilon_m^{N1}\right) = \begin{bmatrix} -2 & a + p_c e_0 \\ a + p_c e_0 & -(1+R)\tau \end{bmatrix}. \tag{A.6}$$

By simple calculating, we find $\det[H(q_m^{N1}, \varepsilon_m^{N1})] > 0$. Thus, by solving $\frac{\partial \pi_m^{N1}}{\partial q_m^{N1}} = 0$ and $\frac{\partial \pi_m^{N1}}{\partial \varepsilon_m^{N1}} = 0$, we can get $q_m^{N1^*} = \frac{\tau(1+R)(u+\theta_0-w^N-w^N R-p_c e_0)}{2\tau(1+R)-(p_c e_0+a)^2}$ and $\varepsilon_m^{N1^*} = \frac{(p_c e_0+a)(u+\theta_0-w^N-w^N R-p_c e_0)}{2\tau(1+R)-(p_c e_0+a)^2}$. Then, Proposition 1 is proved. ☐

Proof of Proposition 2. The proof is similar to Proposition 1. ☐

Proof of Proposition 3. From equations (4) and (5), we can get the optimal pledge rate that can realize the bank's maximum profit satisfies

$$\gamma_b^{N^*} p_c V = w^N q_b^{N^*} + \frac{\tau \varepsilon_b^{N^{*2}}}{2} - B. \tag{A.7}$$

Since the capital-constrained manufacturer does not have speculative motive, he puts all the loan into operation. Denote $\gamma_m^{N1^*}$ and $\gamma_m^{N2^*}$ the minimum pledge rates that can realize the manufacturer's optimal decision when observing good signal and bad signal, respectively. Thus, we have

$$\gamma_m^{N1^*} V p_c = w^N q_m^{N1^*} + \frac{1}{2}\tau \varepsilon_m^{N1^{*2}} - B, \gamma_m^{N2^*} V p_c = w^N q_m^{N2^*} + \frac{1}{2}\tau \varepsilon_m^{N2^{*2}} - B. \tag{A.8}$$

If $\gamma_b^{N^*} \geq {\gamma_m}^{N1^*}$, the manufacturer does not borrow more money even the bank is willing to do so. Then the bank's optimal decision is to set pledge rate on ${\gamma_m}^{N1^*}$. If $\gamma_b^{N^*} < {\gamma_m}^{N1^*}$, providing any pledge rate higher than will increases the bank's bad debt risk. Thus, the bank will choose $\gamma_b^{N^*}$. In a similar way, the case when observing bad signal can be proved. □

Proof of Proposition 4. From equation (7), we can get the manufacturer's optimal decision inferred by the supplier,

$$q_s^{N^*} = \frac{\tau(1+R)\left[(1-r)\left(A_{\mathrm{L}} - \theta_0 - p_c e_0\right) + 2rA_{\mathrm{H}} - w^N(1+r+rR+R)\right.}{(1+r)\left[2\tau(1+R) - (p_c e_0 + a)^2\right]} \tag{A.9}$$

$$\varepsilon_s^{N^*} = \frac{(p_c e_0 + a)\left[(1-r)\left(A_{\mathrm{L}} - \theta_0 - p_c e_0\right) + 2rA_{\mathrm{H}} - w^N(1+r+rR+R)\right.}{(1+r)\left[2\tau(1+R) - (p_c e_0 + a)^2\right]}. \tag{A.10}$$

Substituting (A.9) and (A.10) into (8), then, taking the first and second derivatives of π_s^N with respect to w^N, we get

$$\frac{\partial \pi_s^N}{\partial w^N} = \frac{\tau(1+R)\left[(1-r)\left(A_{\mathrm{L}} - \theta_0\right) - p_c e_0(1+r) + 2rA_{\mathrm{H}} + c(1+r)(1+R) - 2w^N(1+r+rR+R)\right]}{(1+r)\left[2\tau(1+R) - (p_c e_0 + a)^2\right]} \tag{A.11}$$

$$\frac{\partial^2 \pi_s^N}{\partial w^{N2}} = -\frac{2\tau(1+R)^2}{2\tau(1+R) - (p_c e_0 + a)^2}. \tag{A.12}$$

Thus, π_s^N is a concave function of w^N. Let $\frac{\partial \pi_s^N}{\partial w^N} = 0$, denote w^{N^*} the optimal wholesale price in no information sharing scenario, we get

$$w^{N^*} = \frac{(1-r)\left(A_{\mathrm{L}} + \theta_0\right) + 2rA_{\mathrm{H}} - p_c e_0(1+r) + c(1+r)(1+R)}{2(1+r)(1+R)}.$$

□

Proof of Proposition 5. Proposition 5(a). Similar with Proposition 1, we can get the manufacturer's responsive functions of wholesale price w^{PS1} as below.

$$q_m^{\mathrm{PS1}} = \frac{\tau(1+R)\left(u + \theta_0 - w^{\mathrm{PS1}} - w^{\mathrm{PS1}}R - p_c e_0\right)}{2\tau(1+R) - (p_c e_0 + a)^2} \tag{A.13}$$

$$\varepsilon_m^{\mathrm{PS1}} = \frac{(p_c e_0 + a)\left(u + \theta_0 - w^{\mathrm{PS1}} - w^{\mathrm{PS1}}R - p_c e_0\right)}{2\tau(1+R) - (p_c e_0 + a)^2}. \tag{A.14}$$

Substituting (A.11) into (11), then, taking the first and second derivatives of π_s^{PS1} with respect to w^{PS1}, we get

$$\frac{\partial \pi_s^{\mathrm{PS1}}}{\partial w^{\mathrm{PS1}}} = \frac{\tau(1+R)\left[u + \theta_0) - p_c e_0 + c(1+R) - 2w^{\mathrm{PS1}}(1+R)\right.}{2\tau(1+R) - (p_c e_0 + a)^2} \tag{A.15}$$

$$\frac{\partial^2 \pi_s^{\mathrm{PS1}}}{\partial w^{\mathrm{PS1}}2} = -\frac{2\tau(1+R)^2}{2\tau(1+R) - (p_c e_0 + a)^2}. \tag{A.16}$$

Let $\frac{\partial \pi_s^{\mathrm{PS1}}}{\partial w^{\mathrm{PS1}}} = 0$, we get $w^{\mathrm{PS1}^*} = \frac{u+\theta_0-p_c e_0+c(1+R)}{2(1+R)}$.

By substituting w^{PS1^*} into (A.11) and (A.12), we get $q_m^{\mathrm{PS1}^*} = \frac{\tau(1+R)(u+\theta_0-c-cR-p_c e_0)}{4\tau(1+R)-2(p_c e_0+a)^2}$ and $\varepsilon_m^{\mathrm{PS1}^*} = \frac{(p_c e_0+a)(u+\theta_0-c-cR-p_c e_0)}{4\tau(1+R)-2(p_c e_0+a)^2}$.

Denote ${\gamma_m}^{\mathrm{PS1}^*}$ the minimum pledge rate that can realize the manufacturer's optimal decision in partial information sharing scenario, then,

$$\gamma_m^{\mathrm{PS1}^*} V p_c = w^{\mathrm{PS}} q_m^{\mathrm{PS1}^*} + \frac{1}{2}\tau \varepsilon_m^{\mathrm{PS1}^*2} - B. \tag{A.17}$$

When sharing information only with the supplier, the pledge rate that can optimize the bank's profit meets ${\gamma_b}^{\mathrm{PS}^*} = {\gamma_b}^{N^*}$. Then, the final pledge rate is determined by the smaller one, *i.e.*, $\gamma^{\mathrm{PS1}^*} = \min\left[\gamma_b^{N^*}, {\gamma_m}^{\mathrm{PS1}^*}\right]$. ☐

In a similar way, Proposition 5(b) can be proved. ☐

Proof of Proposition 6. The proof is similar to Proposition 3. ☐

Proof of Proposition 7. The proof is similar to Proposition 5. ☐

Proof of Proposition 8. By solving $w^{N^*} - w^{\mathrm{PS1}^*} > 0$, we can get $\theta_0 < \frac{A_{\mathrm{H}}-A_{\mathrm{L}}}{2(1-r)}$. As $w^{\mathrm{PS1}^*} = w^{S1^*}$, thus, there exits $w^{N^*} > w^{\mathrm{PS1}^*} = w^{S1^*}$ if $\theta_0 < \frac{A_{\mathrm{H}}-A_{\mathrm{L}}}{2(1-r)}$. In a similar way, we can prove other relationships among every member's optimal decision when observing good signal.

When partially sharing information with the bank, $q_m^{S2^*} = q_m^{\mathrm{PS2}^*}$. By solving $q_m^{S2^*} - q_m^{N2^*} < 0$, we can get $\theta_0 > \frac{-p_c e_0\left(1-r^2\right)+\left(r-r^2\right)(A_{\mathrm{H}}-A_{\mathrm{L}})}{2r}$. In a similar way, the relationship among other variables can be proved when observing $-\theta_0$. ☐

Proof of Proposition 9. By solving $\pi_m^{S1^*} - \pi_m^{N1^*} \geq 0$, we get $\theta_0 \leq \frac{A_{\mathrm{H}}-A_{\mathrm{L}}}{2(1-r)}$. Comparing $\pi_s^{S1^*}, \pi_s^{\mathrm{PS1}^*}$ and $\pi_s^{N1^*}$, we get $\pi_s^{S1^*} = \pi_s^{\mathrm{PS1}^*} \geq \pi_s^{N1^*}$. By comparing $\pi_m^{S2^*}$ and $\pi_m^{\mathrm{PS2}^*}$, we get $\pi_m^{S2^*} = \pi_m^{\mathrm{PS2}^*}$. By solving $\pi_m^{S2^*} - \pi_m^{N2^*} \geq 0$, we have $\theta_0 \leq \frac{r[A_{\mathrm{H}}(3+r)-A_{\mathrm{L}}(1-r)-2c(1+r)(1+R)]-(1+r)p_c e_0}{2r(2+r)}$. By comparing $\pi_s^{S2^*}$ and $\pi_s^{\mathrm{PS2}^*}, \pi_s^{S2^*} = \pi_s^{\mathrm{PS2}^*}$ holds. By solving $\pi_s^{S2^*} - \pi_s^{N2^*} \geq 0$, we have $\theta_0 \leq \frac{A_{\mathrm{H}}-A_{\mathrm{L}}}{2(1-r)}$. Similarly, the relationship among other variables can be proved. ☐