Under cap-and-trade regulation, this paper investigates information sharing issues in supply chains with different structures. Adopting a game-theoretic method, we start the analysis from a simple bilateral monopoly supply chain with a manufacturer and a retailer. The model is then extended to a scenario with two competing retailers. The manufacturer provides the wholesale price and invests in carbon emission abatement level. The retailers order products to meet consumers’ demand in an uncertain market. One retailer has the power to obtain private information. The results show that the wholesale price and the carbon emission abatement level respond positively to the demand signal. We find that the well-informed retailer is better off with low-demand information sharing and worse off with high-demand information sharing in a bilateral monopoly supply chain. However, the well-informed retailer can benefit from high-demand information sharing in a competitive environment. We also find that the uninformed retailer may get hurt from information sharing under certain conditions. Moreover, the manufacturer’s expected profit is related to the capability of abating carbon emissions, the information accuracy, and the demand uncertainty.

1. Introduction

Carbon emissions associated with rapid economic development have caused many issues, such as global warming and air pollution. Global warming has attracted worldwide concern since it is believed to be a big threat to the health of human beings [1]. Therefore, taking effective measures for curbing carbon emissions is an important task around the world. To achieve the goal, many governments adopt carbon emission regulations, such as carbon cap-and-trade, carbon tax, and low-carbon subsidies. Carbon cap-and-trade is proved to be an effective way to regulate carbon emissions. Under the carbon cap-and-trade mechanism, firms are initially allocated a certain number of carbon emission permits from the government, and they can buy (sell) them in the carbon trading market when necessary. This method has been widely adopted by many areas and governments. For instance, Europe has founded European Union Emissions Trading Scheme (EU ETS), which covers approximately 50% of the total carbon emission in European Union [2]. To reduce carbon emissions, China has planned to establish a national carbon trading market including many industries, such as chemical industry, steel, and electricity. As firms are the main contributors of carbon emissions, they have started to take measures to reduce carbon emissions with carbon cap-and-trade regulation, such as installing emission control equipment and researching new environment-friendly technologies [3].

As it is costly for firms to reduce carbon emissions and to produce eco-friendly products, one significant issue is that whether consumers are willing to pay higher prices for those eco-friendly products. A survey conducted by Toyota reported that the price of hybrid-cars that are able to reduce carbon emissions is 1.5 times higher than that of ordinary cars [4]. It implies that consumers not only pay attention to the price, but also concern about the eco-friendly level when they make purchase decision. In the US, a report claimed that 51% of Americans were willing to pay extra premium for green products [5]. European Commission also reported that 75% of Europeans were willing to buy expensive green products by the year 2008, which increased by 44% compared to the level in 2005 [6]. The more environmental concerns consumers
pay attention to, the higher price consumers are willing to pay for those eco-friendly products [7]. As a result, the stronger willingness to pay higher price for eco-friendly products induces firms to invest in carbon emission abatement.

It is very common that companies are uncertain about market demand and consumers' preferences. The uncertainty is caused by many reasons, such as short lifecycle of electronic products and seasonality of food. One important issue that arises from the uncertainty is how companies better match the market demand, especially for those who sell products through distribution channels. Lack of effective information can result in large losses. Troyer [8] estimated that it costs food service industry approximately $14 billion due to lack of demand information. In such an environment, accessing relevant information can help firms make better decisions on resource utilization. Companies, like Timberland, have established information collecting and demand forecasting platform to cope with demand uncertainty. Another way to solve this problem is to gain information from other companies or clients. Munves [9] documented that firms such as Procter & Gamble and Pepsi buy sales data from their clients. There are also some firms obtaining information shared by their partners. For example, Wal-Mart shared forecast demand information with Warner-Lambert, which smoothed Listerine's production scheduling [10].

With the advance of data collecting technologies, retailers are able to acquire market data easily and precisely. The above examples then raise an interesting question: What are the retailers' incentives to share private information with other firms? Li and Zhang [11] suggest that the well-informed retailers always get hurt from information sharing. Shang et al. [12] investigate an information sharing scenario in which the well-informed retailer charges the suppliers information sharing fee. An interesting issue that rises from the above research (Li and Zhang [11]) is whether a retailer who has superior information always gets hurt from free information sharing. If it does not, under what conditions the well-informed retailer can benefit from information sharing? Does the well-informed retailer have incentive to share information for free in a competing environment? Would the retailer share information with its competitor? Does the uninformed retailer always become better off with information sharing? Under the pressure of carbon emission regulations and consumers' eco-friendly awareness, the manufacturer has to invest in carbon emission abatement. Does information sharing affect the manufacturer's decision on carbon emission abatement? If it does, how does information sharing affect carbon emission abatement?

To address the questions aforementioned, we establish two supply chains with different structures and analyze all the members' decisions in no-information sharing scenario and information sharing scenario. In the models, we assume only one retailer is able to observe the demand forecast. The manufacturer sets the wholesale price and invests in the carbon emission abatement. The retailers compete on order quantities. In the bilateral monopoly supply chain, the results show that the well-informed retailer is better off with low-demand information sharing due to the weakened double marginalization effect but is worse off with high-demand information sharing due to the strengthened double marginalization effect. However, in the supply chain with competing retailers, the well-informed retailer benefits from high-demand information sharing under certain conditions. The results also show that the uninformed retailer may be worse off with information sharing scenario because of the reduced order quantity. We find that sharing high-demand signal increases the carbon emission abatement level set by the manufacturer and sharing low-demand signal lowers the carbon emission abatement level. It is interesting to find that the inefficient manufacturer may charge a lower wholesale price to induce retailers to order more products. The findings also show that the impact of information sharing on the manufacturer is related to the capability of abating carbon emissions.

The reminder of this paper is structured as follows. Section 2 reviews the related literature on cap-and-trade mechanism and information sharing. Section 3 describes the model and presents the notations used in this paper. Section 4 analyzes the bilateral monopoly supply chain with a manufacturer and a well-informed retailer. Section 5 shows the equilibrium analysis in a supply chain with competing retailers. Section 6 provides some numerical examples. We conclude the main findings of this paper and suggest several possible directions for future work in Section 7. All the proofs are collected in the appendix.

2. Literature Review

2.1. Cap-and-Trade Mechanism. To curb carbon emissions, many countries and areas make environmental policies, such as charging carbon tax and making cap-and-trade mechanism. By introducing of carbon taxes, Zakeri et al. [13] establish a supply chain planning model to investigate the impact of operational planning level on supply chain performance. Regulated by carbon tax policy, the retailers' pricing decision and the impacts of carbon costs on the social welfare were studied by Park et al. [14]. With the same carbon emission regulation, Zhou et al. [15] analyze the supply chain members' pricing decisions and find that both the wholesale price and the retail price increase in carbon tax rate. Rosic and Jammernegg [16] structure a model consisting of a single retailer and two suppliers and analyze the retailer's optimal order quantity and sourcing strategy under cap-and-trade and carbon tax, respectively. Yenipazarli [17] finds that a remanufacturer can make more profit under cap-and-trade mechanism than under carbon taxes. In this paper, we assume that a manufacturer produces items under cap-and-trade regulation.

There is substantial literature focusing on the impacts of cap-and-trade on firms' operational decisions. In production and inventory management, Dobos [18] analyzes how emission trading system affects a firm's production and inventory decision and suggests that a firm can sell a certain number of emission permits to smooth production and inventory. Yang et al. [19] construct a two-stage supply chain to study the manufacturer's optimal decision with cap-and-trade policy. Gong and Zhou [20] investigate the impacts of carbon emission trading on firms' production planning and find that
the optimal base-stock level is independent of the emission permits. Cao and Yu [21] analyze the capital-constrained retailer’s optimal ordering quantities under cap-and-trade regulation. Du et al. [22] study an enterprise’s production decision under cap-and-trade regulation. The literature aforementioned studies the inventory problem in a one-to-one supply chain. Differently, we establish a supply chain consisting of one manufacturer and two competing retailers. Moreover, they assume that firms operate under cap-and-trade mechanism without considering emission abatement. In our work, the manufacturer invests in carbon emission abatement to comply with emission regulations.

Besides production and inventory management, researchers are also interested in the pricing strategy from an operational point of view. Xu et al. [23] examine the manufacturer’s optimal pricing decision and the retailers’ order decisions in a make-to-order supply chain in which the manufacturer is regulated by a cap-and-trade regulation. They demonstrate how the purchasing (selling) price of the carbon emission allowance affects the members’ profits. In their work, they do not consider the impacts of carbon emissions on the demand. Considering horizontal competition, Qi et al. [24] investigate the optimal pricing problems of the members’ in a supply chain under the carbon cap regulation. They suggest that the supplier should provide the same wholesale price to the retailers and the retailers should set different retail prices. Similarly, we also establish a supply chain composed of a manufacturer and two competing retailers. Differently, Qi et al. [24] adopt a Bertrand competition, whereas the two retailers compete on quantities in this work and confront the same retail price set by the market. On the other hand, the market demand solely depends on the retail price in Qi et al. [24]. Different from their work, we take the consumers’ environmental awareness into consideration and develop a demand function affected by carbon emission abatement.

Under the pressure of government carbon emission regulations and consumers’ eco-friendly awareness, enterprises make costly effort to abate the environmental impacts of manufacturing. For example, many enterprises design green products or invest in carbon emission abatement during production process [25]. Du et al. [26] investigate a manufacturer’s optimal production strategies on low-carbon products and ordinary products under carbon cap-and-trade regulation. They point out that the manufacturer should take different production strategies according to the unit cost of different kinds of products. In Du et al. [26], they adopt a newsvendor model in which the manufacturer decides both the production quantity and the retail price. Differently, we assume that the manufacturer decides the wholesale price and sells products through retailing channels in this paper. On the other hand, they distinct the low-carbon product by defining lower carbon emissions and higher production cost per unit product. We use the carbon emission abatement level to describe the low-carbon characterization. Considering emission banking strategy, Li [27] investigates the optimal emission abatement effort in a dynamic model. Although the research on investing in emission abatement under cap-and-trade policy is substantial, most of the work does not consider the impact of consumers’ emission sensitivity on the demand. In our model, the demand function is positively affected by carbon emission abatement.

Besides the pressure of governmental emission regulations and public eco-friendly concern, another factor that drives firms to abate carbon emissions is that consumers are willing to pay extra prices for the low-carbon products [28]. Considering consumers’ environmental awareness, Xu et al. [23] design a cost-sharing contract to coordinate the supply chain under carbon cap-and-trade mechanism. These papers analyze emission abatement issues in a one-to-one supply chain. Different from the work above, we consider a supply chain consisting of one manufacturer and two competitive retailers. Zhu and He [1] study the impact of green product types and competition styles on the degree of product greenness. They show that the price competition positively affects the optimal degree of product greenness. In line with their work, we also consider a manufacturer who invests in carbon emission abatement with competing retailers in the market. Our work differs from theirs in at least two dimensions. First, they assume that the information is symmetric, whereas in our work, only one retailer can obtain private information about the market condition. Second, they focus on analyzing how green product types affect emission abatement level. We mainly focus on investigating the impacts of information sharing on operational decisions and the participants’ profits.

2.2. Information Sharing. In operations management area, literature on information sharing focuses on the direct benefits that enterprises gain from sharing information with other supply chain members, including better matching of supply and demand, alleviating bullwhip effect, and reducing capacity costs. For example, Gavirneni [29] shows that changing the managing way of supply chain can make full use of information sharing to reduce cost.

Considering the supply encroachment, Li et al. [30] show that a retailer has incentives to share information with its manufacturer who has encroachment capability. Chen and Deng [31] suggest that an automotive supplier is willing to share its proprietary information with the manufacturer when the information is imprecise. Li [32] is perhaps the first to analyze the incentives of retailers who are in Cournot competition to share private information with the upstream manufacturer. He shows that retailers will not share information voluntarily with the manufacturer. Li and Zhang [11] suggest that retailers have incentives to share information with their manufacturer by signing a confidentiality agreement but do not have incentives to share information publicly. Chen et al. [33] examine the incentive for competing farmers to share demand and price information with each other via a voice-based information service. Shang et al. [12] consider a supply chain consisting of two manufacturers and a retailer and show that large production diseconomy induces more information sharing. Our model shows that the retailer has incentives to share information with the manufacturer to weaken double marginalization and to drive up the carbon emission abatement level. Moreover, the retailer is able to share information publicly under some conditions.
Our work is also related to the literature on the impacts of information sharing. Liao and Chen [34] investigate how the private and public information affects the farmers’ production quantity and their profits. They point out that the public information may be useless under certain conditions when competition exists. Tang et al. [35] analyze how a central planner transmits the market information to the farmers to make higher profit for the group. In the above papers, they do not consider vertical information. Zhang [36] establishes a model with two suppliers and one manufacturer and suggests that the suppliers refuse to share information vertically under some conditions. In this paper, the supplier has private information. Differently, we model a supply chain consisting of a manufacturer and two retailers, and we assume that one retailer has superior demand information. Shang et al. [12] consider a supply chain consisting of two manufacturers and a mutual retailer. They show when a retailer should share information with the manufacturers simultaneously or sequentially. Our work differs from Shang et al. [12] in at least three dimensions. First, in their work, the retailer charges the manufacturers for the demand information, whereas in our work, the retailer shares information for free. Second, in their work, the manufacturers are not regulated by any carbon emission policies; we assume that the manufacturer makes decisions under carbon cap-and-trade regulation. Third, we assume that the manufacturer not only provides the wholesale price but also decides the carbon emission abatement level.

3. The Model

We model a supply chain with a manufacturer (she), an incumbent retailer $i$ (he) who can obtain the demand forecast, and a new entrant retailer $j$ (he) if competition exists in a market characterized by demand uncertainty. The manufacturer provides the wholesale price and invests in reducing carbon emissions. The retailers decide the order quantities in the competitive market.

As discussed in the literature, we know that consumers’ environmental awareness affects consumers’ willingness to pay high price for low-carbon products [6]. As a result, the manufacturer has incentives to invest in carbon emission abatement. They may adopt eco-friendly technologies such as solar technology to reduce carbon emissions, which is often achieved through a one-off investment at the beginning of production. Therefore, we define the cost of carbon emission abatement as $τε^2/2$ [37], where $τ$ stands for the manufacturer’s capability of abating carbon emissions and $ε$ is the carbon emission abatement level. A high coefficient $τ$ means that the manufacturer is inefficient in reducing carbon emissions, and vice versa. The quadratic abatement costs are commonly used in the literature and reflect the diminishing effects on carbon emission abatement [38]. When investing in abating carbon emissions, the total carbon emissions are $(1 - ε)e_0$, where $e_0$ represents the carbon emissions per unit product before investing carbon emission abatement. To facilitate analysis, we follow Ghosh and Shah [39] to assume that the carbon emission abatement investment does not affect the manufacturer’s unit production cost $c$.

To capture the characteristic of consumers’ low-carbon preference, the market clearing price is described as $p = a - q_i - q_j + be$ (see [40]), where $q_i$ and $q_j$ represent retailer $i$’s order quantity and retailer $j$’s order quantity, respectively. The uncertain intercept $a$ takes value $a_H$ with probability $r$ and value $a_L (0 < a_L < a_H)$ with probability $(1 - r)$. The mean demand with prior belief is given as $u = ra_H + (1 - r)a_L$. The distribution of intercept $a$ is common knowledge to all members in the supply chain. The parameter $b$ represents the consumers’ sensitivity to carbon emission abatement. Retailer $i$ has been in the market for a long time and is able to obtain more information about $a$. The signal has two values $s_h$ (high) and $s_l$ (low) with the probability $Pr(s_h | a_H) = ϕ$ and $Pr(s_l | a_L) = ϕ$. We assume $ϕ > 0.5$ to guarantee that the signal observed by retailer $i$ is informative. A larger $ϕ$ means that the forecast is more accurate. Then, the manufacturer updates her belief based on the Bayes rule: $r_h = Pr(a_H | s_h) = rϕ/(rϕ + (1 - r)(1 - ϕ))$, $r_l = Pr(a_L | s_l) = r(1 - ϕ)/(rϕ + (1 - r)(1 - ϕ))$. The updated mean demand is $\bar{u}_x = r_h a_H + (1 - r_l)a_L$ when observing the signal $s_x$, where $x$ can be $h$ or $l$. Then, there exists $u_h > u > u_l$.

The sequence of events is as below, which is depicted in Figure 1. First, the information sharing format is contracted at the beginning: no-information sharing or information sharing. Second, the retailer observes demand signal, which can be high or low. Third, the manufacturer sets the wholesale price and carbon emission abatement according to the information sharing format chosen at the beginning. Fourth, the retailer (retailers) decides (decide) the order quantity. In a competing supply chain, retailer $j$ orders products either simultaneously with retailer $i$ in no-information sharing scenario or after retailer $j$ in information sharing scenario. Thus, we use the dotted line to present retailer $j$’s move. Afterward, the market demand is realized.

We use the superscript $T$ to denote the scenario with two competing retailers and the superscript $Y$ to denote the information sharing format: $Y$ can be $N$ (no-information sharing) and $S$ (information sharing). The notations are presented in Table 1.

4. Bilateral Monopoly Supply Chain

In a bilateral monopoly supply chain, both the manufacturer and retailer $i$ are monopolists in their own area. In this scenario, the retailer can obtain superior demand information because he has access to consumers. The manufacturer relies on the retailer to get updated information.

4.1. No-Information Sharing. In this scenario, the retailer updates his belief according to the signal he observed. The expected profit of the retailer is written as

$$p_{\text{fix}}^N = \left[ E (a_x \mid s_x) - q_{\text{fix}}^N + be^N - w^N \right] q_{\text{fix}}^N. \tag{1}$$

Given the wholesale price $w^N$ and the emission abatement level $e^N$, the retailer optimizes his expected profit by choosing $q_{\text{fix}}^N = (1/2)(u_x + be^N - w^N)$.
Table 1: Notations and explanations.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( q_i )</td>
<td>Retailer ( i )'s order quantity</td>
</tr>
<tr>
<td>( q_j )</td>
<td>Retailer ( j )'s order quantity</td>
</tr>
<tr>
<td>( w )</td>
<td>Wholesale price decided by the manufacturer</td>
</tr>
<tr>
<td>( \varepsilon )</td>
<td>Carbon emission reduction decided by the manufacturer</td>
</tr>
<tr>
<td>( a_z )</td>
<td>Market potential; ( c ) can be ( H ) or ( L )</td>
</tr>
<tr>
<td>( s_x )</td>
<td>Demand signal observed by retailer ( i ); ( x ) can be ( h ) (high) or ( l ) (low)</td>
</tr>
<tr>
<td>( p )</td>
<td>Retail price per unit product</td>
</tr>
<tr>
<td>( c )</td>
<td>Production cost per unit product</td>
</tr>
<tr>
<td>( e_0 )</td>
<td>Carbon emissions per unit product</td>
</tr>
<tr>
<td>( r )</td>
<td>Prior belief about high demand state</td>
</tr>
<tr>
<td>( r_x )</td>
<td>Updated belief about high demand state when observing ( s_x )</td>
</tr>
<tr>
<td>( \phi )</td>
<td>Probability of observing ( s_x )</td>
</tr>
<tr>
<td>( u_x )</td>
<td>Prior mean demand</td>
</tr>
<tr>
<td>( \tau )</td>
<td>Investment coefficient of carbon emission abatement</td>
</tr>
<tr>
<td>( b )</td>
<td>Consumers’ sensitivity to carbon emission abatement</td>
</tr>
<tr>
<td>( k )</td>
<td>Carbon price</td>
</tr>
<tr>
<td>( G )</td>
<td>Carbon cap allocated by the government</td>
</tr>
<tr>
<td>( \pi_m )</td>
<td>Manufacturer’s expected profit</td>
</tr>
<tr>
<td>( \pi_i )</td>
<td>Retailer ( i )'s expected profit</td>
</tr>
<tr>
<td>( \pi_j )</td>
<td>Retailer ( j )'s expected profit</td>
</tr>
<tr>
<td>( \Pi )</td>
<td>Profit of the entire supply chain</td>
</tr>
</tbody>
</table>

The uninformed manufacturer makes decisions based on her prior belief about the market condition. Thus, her expected profit is given by

\[
\pi_m^N = (w^N - c) E(q_{ix}^N) + k \left[ G - (1 - \varepsilon^N) e_0 E(q_{ix}^N) \right] - \frac{1}{2} \tau (\varepsilon^N)^2,
\]

where the expectation operator \( E(q_{ix}^N) = (1/2)(u + b e_0 - w^N) \).

In (2), the three bracketed terms are sales profit in the product market, the revenue (cost) in the carbon market, and the investment cost of carbon emission abatement, respectively.

Define \( \rho = \frac{u_L - c - ke_0}{(a_L - c - ke_0)} \) as the proxy of demand uncertainty, which approximately measures the distance between the high-demand state and the low-demand state. The next proposition presents each participant’s optimal decision in no-information sharing scenario.

**Proposition 1.** Assuming \( r_l/r > (2\tau - (b + ke_0)^2)/(4\tau - (b + ke_0)^2) \) or \( r_l/r < (2\tau - (b + ke_0)^2)/(4\tau - (b + ke_0)^2) \) and \( \rho < (2\tau(1 - r_l) + (r_l - r)(2\tau - (b + ke_0)^2))/((2\tau - (b + ke_0)^2)r - [4\tau - (b + ke_0)^2]r_l) \), we get the following:

(a) the optimal carbon emission abatement is \( e_{ix}^{N*} = (b + ke_0)(u - c - ke_0)/(4\tau - (b + ke_0)^2) \), and the optimal wholesale price is \( w_{ix}^{N*} = (u(2\tau - k^2e_0^2 - bke_0) + (2\tau - b^2 - bke_0)(c + ke_0))/(4\tau - (b + ke_0)^2) \).

(b) the retailer’s optimal order quantity is \( q_{ix}^{N*} = u/2 + ((ke_0 + b)^2 - 2\tau u - 2\tau(c + ke_0))/(8\tau - 2(b + ke_0)^2) \).

The conditions \( r_l/r > (2\tau - (b + ke_0)^2)/(4\tau - (b + ke_0)^2) \) or \( r_l/r < (2\tau - (b + ke_0)^2)/(4\tau - (b + ke_0)^2) \) and \( \rho < (2\tau(1 - r_l) + (r_l - r)(2\tau - (b + ke_0)^2))/((2\tau - (b + ke_0)^2)r - [4\tau - (b + ke_0)^2]r_l) \) guarantee the retailer’s participation when observing low-demand signal. The condition \( 4\tau > (b + ke_0)^2 \) guarantees that the decision variables are positive. Proposition 1(a) demonstrates
the manufacturer's optimal decisions under no-information sharing. The results show that the carbon emission abatement increases in the consumers' environmental sensitivity since the consumers who are more environmentally sensitive are willing to pay higher price. Note that the mean market potential \( u \) is much larger than \( c, ke_0 \), and \( b \). Then, by judging \( \delta \varepsilon^N/\delta \varepsilon = 2(b + ke_0)(u - c - x)/(4\tau - (b + ke_0)^2)\) + \((u - c - 2x - b)/(4\tau - (b + ke_0)^2) > 0\), we get that the carbon emission abatement also increases in the carbon price since it costs the manufacturer much to buy carbon emission permits in the carbon market if the carbon cap is not enough to cover the total emissions. In contrast, she can obtain much revenue when she sells the extra emission permits. The result also shows that the optimal carbon emission abatement decreases with the investment coefficient because the manufacturer will lower the abatement level to cut costs if she is not efficient in reducing carbon emissions.

From Proposition 1(a), we find that the optimal wholesale price increases with consumers' environmental sensitivity if \( \tau > ke_0(b + ke_0)^2/4b \), and it decreases with consumers' environmental sensitivity if \( \tau < ke_0(b + ke_0)^2/4b \). Note that the demand increases in consumers' environmental sensitivity, and high environmental sensitivity promotes the market demand. When the manufacturer is inefficient in abating carbon emissions, i.e., \( \tau > ke_0(b + ke_0)^2/4b \), it costs the manufacturer too much to produce more items. As a result, the manufacturer has to charge a higher wholesale price to cover the total costs. Interestingly, we find that the wholesale price \( w^N \) increases in \( \tau \) if \( b < ke_0 \), but it decreases in \( \tau \) if \( b > ke_0 \). The inequality \( b < ke_0 \) means that the profit margin of carbon emission abatement is less than the cost margin of carbon emissions. In this case, the manufacturer will set a higher wholesale price to induce a lower order quantity to cut the profit loss. When \( b > ke_0 \), the profit margin of carbon emission abatement outweighs the cost margin; although the investment coefficient increases, the manufacturer can still charge a lower wholesale price to induce the retailer to order more products.

Part (b) presents the retailer’s optimal ordering strategy in no-information sharing scenario. It shows that the optimal order quantity increases with the environmental sensitivity since the consumers prefer to buy low-carbon products. The results also show that the optimal order quantity decreases in the investment coefficient. With the investment coefficient increasing, the manufacturer lowers the carbon emission abatement level, which reduces the order quantity because the lowered carbon emission abatement level reduces the consumers’ demand. We also find that the relationship between the optimal order quantity and the carbon price is inconclusive. If \( \tau < (b + ke_0)(u + b - 2c - 2ke_0)/3 \), the optimal order quantity increases with the carbon price; otherwise, it decreases with the carbon price. The intuition behind this result is that the efficient manufacturer sets a higher carbon emission abatement level. As a result, the retailer orders more products to meet consumers’ demand driven by the higher emission abatement level. Otherwise, the retailer has to reduce the order quantity.

### 4.2. Information Sharing Scenario

We now turn to analyze each member's decision in an information sharing scenario. In this case, the manufacturer updates her belief about the high market condition based on the information shared by the retailer. Given the wholesale price and the carbon emission abatement level, the retailer’s expected profit is written as

\[
\pi^s_{lx} = \left[ E(a_x | s_x) - q^s_x + b e^s_x - w^s_x \right] q^s_{lx}.
\]

Similar to no-information sharing scenario, the retailer optimizes his expected profit by choosing \( q^s_{lx} = (1/2)(u_x + be^s_x - w^s_x) \).

Under information sharing, the manufacturer makes decisions based on the updated information. Then, her expected profit is described as

\[
\pi^s_{mx} = \left[ (\omega^s_x - c) q^s_x + k \left[ G - (1 - \varepsilon^s_x) e^s_0 q^s_x \right] \right] - \frac{1}{2} \tau (\varepsilon^s_x)^2.
\]

The following proposition describes the members’ optimal decisions under information sharing.

**Proposition 2.** (a) When information is shared, the optimal carbon emission abatement set by the manufacturer is \( e^s_0 = (b + ke_0)(u_x + c - ke_0)/(4\tau - (b + ke_0)^2) \), and the optimal wholesale price is \( w^s_x = (u_x(2\tau - b^2 - bke_0) + (2\tau - b^2 - bke_0)(c + ke_0))/(4\tau - (b + ke_0)^2) \).

(b) The optimal order quantity is \( q^s_{lx} = \tau(u_x - c - ke_0)/(4\tau - (b + ke_0)^2) \).

Compared with no-information sharing scenario, we find that the wholesale price and carbon emission abatement level respond positively to the demand signal. Specifically, the manufacturer sets a high carbon emission abatement level and a high wholesale price when receiving high-demand signal; she invests in a low emission abatement level and charges a low wholesale price when receiving low-demand signal. Compared with no-information sharing scenario, we find that sharing low-demand information increases the retailer’s order quantity. When sharing low-demand signal, although the carbon emission abatement level is lowered, the retailer benefits from the lowered wholesale price and increases his order quantity eventually. In contrast, when sharing high-demand signal, the effect of higher carbon emission abatement is weaker than the double marginalization effect; thus, the retailer decreases his order quantity.

### 4.3. Implications of Information Sharing

So far we have analyzed the optimal decisions of each member in different information sharing formats. In this subsection, we try to analyze the impacts of information sharing on every participant’s expected profit. Based on the analysis in Sections 4.1 and 4.2, we can get each member’s profits in different scenarios as follows. The retailer’s expected profits are
The expected profits of the entire supply chain are always hurt from information sharing. As a result, sharing high-demand signal hurts the manufacturer, she can always benefit from a high wholesale price. Thus, sharing high-demand information results in two abatement effects. On the retailer level, the manufacturer benefits from the lowered wholesale price. When the retailer observes the high-demand signal, sharing information, based on the prior belief, she makes her decision in no-information sharing scenario. No-Information Sharing Scenario. Theorem 3(b) complements the effect of information sharing when observing the low-demand signal, but he gets hurt from sharing the high-demand signal. Since retailer \( i \) is able to observe the demand signal, he makes his decision based on the signal \( s_x \) and his expected profit is given by

\[
\pi_{ix}^{TN} = (E(a \mid s_x) - q_{ix}^{TN} - d_j^{TN} + be - w)q_{ix}^{TN}. 
\]

Retailer \( j \) makes decision based on the prior belief; thus, his expected profit is written as

\[
\pi_j^{TN} = (E(a) - q_j^{TN} - d_j^{TN} + be - w)q_j^{TN}. 
\]

As no information is shared between the retailers, they place orders simultaneously. Thus, retailer \( i \)'s order quantity is \( q_{ix}^{TN} = (3u_x - u - 2w + be)/6 \), and retailer \( j \)'s order quantity is \( q_j^{TN} = (u - w + be)/3 \). As the manufacturer also does not have updated demand information, based on the prior belief, she makes her decision to maximize her expected profit

\[
\pi_m^T = (w - c)E(q_{ix}^{TN}) + E(q_j^{TN}) + k\left(G - (1 - e)\epsilon_0 [E(q_{ix}^{TN}) + E(q_j^{TN})]\right) 
\]

\[-\frac{1}{2}\epsilon_0^2.\]

The next proposition describes all the members’ optimal decisions under no-information sharing scenario.

Proposition 4. Assuming \( r_j/r < (2\tau - (b + ke_0)^2)/(3\tau - (b + ke_0)^2) \) and \( \rho < \tau/(r[2\tau - (b + ke_0)^2] - r_j[3\tau - (b + ke_0)^2]) \) or \( r_j/r > (2\tau - (b + ke_0)^2)/(3\tau - (b + ke_0)^2) \), then

(a) the optimal carbon emission abatement level is \( e_{TN}^* = (b + ke_0)(u - c - ke_0)/(3\tau - (b + ke_0)^2) \), and the optimal wholesale price is \( w_{TN}^* = (u(3\tau - 2k^2e_0^2 - 2bk^{2}e_0) + (3\tau - 2\beta^2 - 2bk^{2}e_0)(c + ke_0))/(6\tau - 3(b + ke_0)^2); \)

5. A Supply Chain with Competing Retailers

In this section, we consider a supply chain with a mutual manufacturer and two competing retailers who compete for order quantities. We assume that retailer \( i \) is able to observe the demand signal since he has been in the market for a long time, and the other retailer \( j \) is a new entrant retailer who only has the common knowledge about the market condition. The superscript \( T \) stands for the scenario with two competing retailers. We start our analysis by discussing every party’s strategy in no-information sharing scenario.
(b) retailer i's order quantity is \( q^*_i \) and \( u_i \) are:

\[
q^*_i = \left( u_i \right) \left( \frac{3\tau - (b + ke_0)^2}{2\tau - (b + ke_0)^2} \right) - \left( 3\tau - 2(b + ke_0)^2 \right) \text{ and retailer j's order quantity is } q^*_j = \tau \left( u_j - c - ke_0 \right) / (6\tau - 2(b + ke_0)^2) \text{.}
\]

The conditions \( r_i / r < (2\tau - (b + ke_0)^2) / (3\tau - (b + ke_0)^2) \) and \( \rho < (\tau / (r[2\tau - (b + ke_0)^2])) \text{ or } r_i / r > (2\tau - (b + ke_0)^2) / (3\tau - (b + ke_0)^2) \) guarantee retailer i's participation in no-information sharing scenario. Comparing with the order quantity in no-information sharing scenario in Section 4.1, we find that both the carbon emission abatement level and the wholesale price are higher in the competing situation. The reason is that the competition between the retailers enhances the cumulative order quantities in the market.

By substituting \( e^T_N \) and \( w^T_N \) into the retailers' order quantities, we can get that the retailers' equilibrium decisions are \( q^T_N \) and \( q^T_N \). Comparing with the order quantity in no-information sharing scenario, we find that the well-informed retailer i decreases his order quantity regardless of observing high- or low-demand signal, which is caused by the fierce competition between the retailers.

5.2. Information Sharing Scenario. In this subsection, we assume that retailer i shares information publicly, which means he also conveys information to the uninformed retailer j. If retailer i shares information only with the manufacturer, the uninformed retailer can infer information from the wholesale price. Therefore, he chooses to share information publicly. In this case, the uninformed retailer j moves after retailer i to ensure truthful information sharing. Based on the updated information and the well-informed retailer's action, retailer j's expected profit is given by

\[
\pi^T_{jx} = \left( E(a | s_x) - q^T_{ix} - q^T_{jx} + be - w \right) q^T_{jx} \text{.} \tag{12}
\]

Then, we get \( q^T_{ix} = \left( u_x - q^T_{ix} - w + be / 2 \right) / 2 \). Given the response function of retailer j, the expected profit of retailer i is described as

\[
\pi^T_{ix} = \left( E(a | s_x) - q^T_{ix} - q^T_{jx} + be - w \right) q^T_{ix} \text{.} \tag{13}
\]

Based on (12) and (13), we obtain that the optimal decision of retailer i is \( q^T_{ix} = \left( u_x - w + be / 2 \right) \), and the optimal order quantity of retailer j is \( q^T_{jx} = \left( u_x - w + be / 4 \right) \).

Anticipating the retailers' order quantities, the manufacturer optimizes her expected profit by choosing \( e \) and \( w \). Her expected profit is given by

\[
\pi^T_{mx} = (w - c) \left( q^T_{ix} + q^T_{jx} \right) + k \left[ G - (1 - e) e_0 \left( q^T_{ix} + q^T_{jx} \right) \right] - \frac{1}{2} \tau^2 \epsilon^2 \text{.} \tag{14}
\]

Then, we can get every party's optimal strategy in the information sharing scenario, which is described in Proposition 5.

**Proposition 5.** (a) The optimal carbon emission abatement is \( e^T_N = 3(b + ke_0)(u_x - c - ke_0) / (8\tau - 3(b + ke_0)^2) \), and the optimal wholesale price is \( w^T_N = \left( u_i (4\tau - 3k^2 e_0^2 - 3b e_0) + (4\tau - 3b^2 - 3b e_0) (c + ke_0) \right) / (8\tau - 3(b + ke_0)^2) \).

(b) Retailer i's optimal order quantity is \( q^T_{ix} = 2(\tau (u_x - c - ke_0)) / (8\tau - 3(b + ke_0)^2) \), and retailer j's optimal order quantity is \( q^T_{jx} = \tau (u_j - c - ke_0) / (8\tau - 3(b + ke_0)^2) \).

Proposition 5(a) demonstrates the manufacturer's optimal decisions when the retailers engage in a sequential-move in an information sharing scenario. The results show that both the optimal carbon emission abatement and the optimal wholesale price are larger than those in the no-competing scenario in Section 4.2 since the competition between the retailers enhances the cumulative order quantities. Part (b) shows that both retailers' order quantities are related to the updated mean demand under information sharing. It also shows that retailer i orders more products than retailer j by taking the advantage of being the first-mover. Compared with the manufacturer's decisions in no-information sharing scenario in Section 5.1, we can get the following proposition.

**Proposition 6.** \( e^T_N > e^T_N \) if \( r_i / r > (8\tau - 3(b + ke_0)^2) / (9\tau - 3(b + ke_0)^2) \); \( w^T_N > w^T_N \) if \( b < ke_0 \) and \( r_i / r > (6\tau - 2(b + ke_0)^2) / (9\tau - 3(b + ke_0)^2) \); \( \epsilon^T_N > \epsilon^T_N \) if \( b > ke_0 \) and \( r_i / r > (6\tau - 2(b + ke_0)^2) / (9\tau - 3(b + ke_0)^2) \).

Proposition 6 demonstrates how information sharing affects the manufacturer's optimal decisions. The results show that when sharing the low-demand signal, the change of the carbon emission abatement level is uncertain. With imprecise demand signal, i.e., \( r_i / r > (8\tau - 3(b + ke_0)^2) / (9\tau - 3(b + ke_0)^2) \), the emission abatement level in the information sharing scenario is higher than that in no-information sharing scenario. Note that sharing the low-demand information induces the manufacturer to set lower carbon emission abatement level, whereas the sequential-move drives up the carbon emission abatement level. When the low-demand information is imprecise, the effect of information sharing is weaker than the effect of sequential-move. As a result, the manufacturer invests in a relatively high emission abatement level. In contrast, if the low-demand information is precise, the manufacturer invests in a lower emission abatement level. For the wholesale price, we find that \( w^T_N < w^T_N \) if \( b > ke_0 \). When \( b > ke_0 \), the benefit of selling one unit product is higher than the cost of producing one unit item. Therefore, the manufacturer tends to provide a lower wholesale price to induce the retailers to order more products. The results also show that both the carbon emission abatement level and the wholesale price increase when observing high-demand signal. The intuition behind this result is that retailer i takes the advantage of being the first-mover, which increases the total order quantities. Consequently, the manufacturer charges a high wholesale price and sets a high carbon emission abatement level.
Comparing the retailers’ order quantities in the information sharing scenario with those in no-information sharing scenario, we can get Proposition 7.

**Proposition 7.** \( q_{TS}^{TN_i} > q_{TN_i}^{TN_i} > q_{TS}^{TN_j} > q_{TN_j}^{TN_j} \) if \( \tau > 3(b + ke_0)^2/2 \) or \( \tau > 3(b + ke_0)^2/2 \) and \( r_i/r > A \) and \( \rho > (A - 1)/(r_i - Ar) \), where \( A = [8(3 - (b + ke_0)^2)(3b + ke_0)^2]/[3\tau - (b + ke_0)^2][2\tau - (b + ke_0)^2] \). \( q_{TS}^{TN_i} > q_{TN_i}^{TN_i} > q_{TS}^{TN_j} > q_{TN_j}^{TN_j} \) if \( r_i/r > (8\tau - 3(b + ke_0)^2)/(6\tau - 2(b + ke_0)^2) \) and \( \rho > 1 + 2(\tau - (b + ke_0)^2)/(r_i[6\tau - 2(b + ke_0)^2] - [8\tau - 3(b + ke_0)^2]). \)

When observing the low-demand signal, compared with no-information sharing scenario, the retailer increases his order quantity due to being the first-mover and the weakened competition. When observing the high-demand signal, the relationship between \( q_{TS}^{TN_i} \) and \( q_{TN_i}^{TN_i} \) depends on the carbon emission abatement efficiency, accuracy of demand forecast, and the demand uncertainty. If the manufacturer is efficient in abating carbon emissions, retailer i’s order quantity increases because of the high market demand promoted by a high carbon emission abatement level. When the manufacturer is not very efficient in reducing carbon emissions, retailer i still orders more products if the information accuracy and demand uncertainty are high. This is because retailer i can get more profit if the realized demand is high. For retailer j, sharing low-demand information reduces his order quantity. However, when sharing high-demand information, retailer j’s order quantity may be enhanced. If the information accuracy and demand uncertainty are large, the benefit to retailer j of obtaining high-demand information outweighs the cost of being the last-mover. As a result, retailer j tends to place a larger order.

Comparing every member’s expected profits in different information sharing scenarios, we can obtain the theorem that describes the effects of information sharing when observing low-demand signal.

**Theorem 8.** (a) Low-demand information sharing always benefits retailer i.

(b) Low-demand information sharing always hurts retailer j.

(c) When \( (8\tau^2 - 9r_j^2)/(3\tau^2 - 3r_j^2) > 0 \), low-demand information sharing benefits the manufacturer if \( (b + ke_0)^2 < (8\tau^2 - 9r_j^2)/(3\tau^2 - 3r_j^2) \) and \( \rho < \rho' \) or \( (8\tau^2 - 9r_j^2)/(3\tau^2 - 3r_j^2) < (b + ke_0)^2 \), where \( \rho' = 1 + \sqrt{(3\tau - r_j^2)(8\tau - 3(b + kg)^2)/(3\tau - r_j^2) - 3(b + kg)^2} + 8\tau - 9r_j)/((3(b + kg)^2(r - r_j) + 8\tau - 9r_j)/(3\tau - r_j^2)(r - r_j^2) - 8\tau^2 r + 9\tau r_j^2).

Similar to the bilateral monopoly scenario, sharing the low-demand signal always benefits retailer i since the competition is weakened. For retailer j, sharing low-demand information lowers his order quantity. On the other hand, being the last-mover further decreases his order quantity. As a result, retailer j always gets hurt from low-demand information sharing. For the manufacturer, the impacts of information sharing depend on the information accuracy, the efficiency of carbon emission abatement, and the demand uncertainty. The condition \( (8\tau^2 - 9r_j^2)/(3\tau^2 - 3r_j^2) > 0 \) implies that the information is not very accurate.

Different from the bilateral monopoly scenario, we find that the manufacturer can become better off from low-demand information sharing. When the manufacturer is not efficient in abating emissions, i.e., \( (b + ke_0)^2 < (8\tau^2 - 9r_j^2)/(3\tau^2 - 3r_j^2) \), she benefits from information sharing if the demand uncertainty \( \rho < \rho' \). In this case, the sequential-move can drive up the cumulative order quantities. Although the wholesale price is lowered, the manufacturer benefits from cost saving of abating carbon emissions and the increased total order quantities. When the manufacturer is efficient in carbon emission abatement, she is always better off with information sharing because the higher emission abatement level promotes consumers’ demand.

So far we have analyzed the effect of low-demand information sharing: the following theorem presents the effects of high-demand information sharing on every member in the supply chain.

**Theorem 9.** (a) High-demand information sharing benefits retailer i if \( r < r_0 \) and \( \rho < \rho_0 \) or \( r_0 < r < r_0 \), where \( r_0 = (3\tau/\beta(b + kg)^2 - \tau)/(17 - 2\tau)(b + kg)^2 + \tau(17 - 2\tau)/((3\tau^2 - 3r_j^2)(8\tau - 3(b + kg)^2)/(3\tau - r_j^2) - 3(b + kg)^2]) > 0 \). 

(b) High-demand information sharing benefits retailer j if \( r < r_1 \) and \( \rho > \rho_1 \) or \( r_1 < r < 3\tau/4 \) and \( \rho < \rho_1 \), where \( r_1 = (6\tau r_j - 2r_j(b + kg)^2)/(8\tau - 3(b + kg)^2) \) and \( \rho_1 = (2\tau(1 - 4\tau + 3r_j)/((6\tau - 8\tau(r_j + 9\tau)/(b + kg)^2(1 - 3r_j^2 + 2r_j))/(6\tau - 8\tau(r_j + 9\tau)/(b + kg)^2(3\tau - 2r_j)) \).

(c) High-demand information sharing always benefits the manufacturer.

Theorem 9(a) presents the effect of information sharing on retailer i when he observes high-demand signal. The result shows that retailer i does not always get hurt from high-demand information sharing. When the prior belief upon the high-demand state is less than \( r_0 \), retailer i can benefit from information sharing if the demand uncertainty is small. The reason is that the benefits of increased carbon emission abatement level and being the first-mover to retailer i outweigh the cost of strengthened double marginalization. When the prior belief of the high-demand condition is relatively high, the competition between the retailers is weakened, which also benefits retailer i.

Theorem 9(b) shows that high-demand information sharing benefits retailer j under some conditions. Specifically, when the prior belief on the high-demand state is quite low, he benefits from information sharing if the demand uncertainty is large. In this case, sharing high-demand signal enhances the order quantity of retailer j. As a result, retailer j can benefit from the increased sales volume. When the prior belief of the high-demand state is high, retailer j benefits from information sharing if the demand uncertainty is small, because the benefit of information sharing effect to retailer j outweighs the effect of being the last-mover. From the perspective of the manufacturer, she is always better off with information sharing since sharing high-demand
information induces the manufacturer to set a high wholesale price.

6. Numerical Examples

In this section, we examine the impacts of the prior belief $r$, carbon price $k$, and the updated belief $\phi$ on the members and the supply chain performance. We set $a_H = 500$, $a_L = 200$, $e_0 = 1$, $G = 100$, $r = 10000$, $b = 20$, $c = 10$, $\phi = 0.8$, $k = 2$, $r = 0.6$. When analyzing one of the three parameters ($r, k, \phi$), the other two parameters are fixed.

The first set of examples examines how the prior belief $r$ affects each member's profit and the supply chain performance in a bilateral monopoly supply chain. In this set of examples, we fix $\phi = 0.8$, $k = 2$. Figure 2(a) shows that the retailer's expected profits increase in the prior belief $r$ regardless of no-information sharing scenario or information sharing scenario. The reason is that the mean demands $u_l$ and $u$ increase in the prior belief $r$. With a higher prior belief, the retailer tends to order more products to supply a brisk market, which increases his expected profit eventually. Figure 2(a) also shows that the retailer's expected profit in an information sharing scenario is higher than that in no-information sharing scenario. It implies that the retailer benefits from low-demand information sharing, which is consistent with Theorem 3(a).

For the manufacturer, she will charge a higher wholesale price to earn more profits with the prior belief $r$ increasing, which is shown in Figure 2(b). As sharing low-demand signal induces the manufacturer to provide a low wholesale price, she gets hurt from information sharing in this scenario. When the decrement of the manufacturer's expected profit exceeds the increment of the retailer's expected profit, the performance of the supply chain declines, as shown in this numerical example. Otherwise, the supply chain performance is better off.

When observing a high-demand signal, the impacts of the prior belief $r$ are shown in Figure 3. Figure 3(a) shows that $\pi_{th}^{N^*}$ increases in $r$ first and decreases in $r$ after reaching the maximum value. When $r < r_1$, the retailer can benefit from a lower wholesale price, while when $r > r_1$, the wholesale price is much higher with $r$ increasing. In this case, the retailer's expected profit decreases in $r$. Figure 3(b) shows that the expected profit of the manufacturer increases with $r$ when receiving a high-demand signal, whereas the increment speed is lower and lower due to the strengthened double marginalization effect. When sharing high-demand signal, the manufacturer updates her prior belief and charges a high wholesale price. Thus, she can benefit from information sharing; i.e., $\pi_{mh}^{N^*} > \pi_{ml}^{N^*}$, which is depicted in Figure 3(b). In this scenario, the increment of the manufacturer's expected profit outweighs the decrement of the retailer's expected profit; thus, the entire supply chain is better off with information sharing.

The second set of numerical examples shows the impacts of carbon price on the carbon emission abatement and the order quantities in a supply chain with competing retailers. In this case, we fix $\phi = 0.8$, $r = 0.6$. Figure 4 depicts the relationship between carbon emission abatement level $\varepsilon$ and carbon price $k$. It shows that the carbon emission abatement level increases with carbon price. The reason is
that buying (selling) carbon emission permits increases the manufacturer's cost (revenue). Therefore, the manufacturer tends to invest in higher carbon emission abatement with a higher carbon price. Given the parameters set in Section 6, we find that 
\[
\frac{r_l}{r} < \frac{(8\tau - 3(b + ke_0)^2)}{(9\tau - 3(b + ke_0)^2)}.
\]
Thus, 
\[
\varepsilon_{l}^{TS} < \varepsilon_{l}^{TN} < \varepsilon_{l}^{TS},
\]
as shown in Figure 4. It implies that sharing low-demand signal lowers the carbon emission abatement level and sharing high-demand signal increases the carbon emission abatement level, because a good market prospect promotes the manufacturer to
invest in high emission abatement level to increase market demand.

With low-demand signal, Figure 5(a) shows that both retailers’ order quantities decrease with \( k \) regardless of the no-information sharing scenario or the information sharing scenario. When the carbon price is high, the manufacturer will enhance wholesale price to complement the cost from the carbon market. In the low-demand state, the retailers have to cut the order quantities to save costs. Figure 5(a) also shows that sharing low-demand signal increases retailer \( i \)’s order quantity, whereas retailer \( j \)’s order quantity is reduced. This is because information sharing weakens the competition between the retailers. On the other hand, retailer \( i \) also benefits from being the first-mover. Similarly, the scenario with high-demand signal can be analyzed. Interestingly, a weak U-shaped relationship is found between the retailers’ order quantities and the carbon price \( k \) when sharing high-demand signal. This is because when the carbon price is high, the manufacturer will invest in a high carbon emission abatement level, which increases consumers’ demand. In this case, the retailers will increase their order quantities.

The last set of numerical examples presents how the probability \( \phi \) affects every participator’s profit and the supply chain performance in a competitive setting. In this case, we fix \( r = 0.6, k = 2 \). To ensure retailer \( i \)’s participation in no-information sharing scenario when observing a low-demand signal, we assume \( \phi < 0.85 \). From Figure 6(a), we can see that retailer \( i \)’s expected profit decreases with \( \phi \) both in no-information sharing scenario and information sharing scenario. When observing a low-demand signal, retailer \( i \) decreases his order quantity to avoid over-order. The larger the probability \( \phi \) is, the smaller \( q_{TN}^{TN*} \) and \( q_{TN}^{TS} \) are. Consequently, retailer \( i \)’s expected profit decreases \( \phi \). For retailer \( j \), he makes decision based on the prior belief in no-information sharing scenario. Thus, \( \pi_j^{TN*} \) is independent of probability \( \phi \). When information is shared, similar to retailer \( i \), retailer \( j \)’s profit also decreases with \( \phi \). Figure 6(a) also shows that retailer \( i \) benefits from low-demand information sharing, whereas retailer \( j \) gets hurt from low-demand information sharing. The results are consistent with Theorem 8(a) and (b).

Figure 6(b) presents the impacts of \( \phi \) on the manufacturer and the entire supply chain when observing a low-demand signal. When \( \phi < \phi_2 \), the manufacturer benefits from low-demand information sharing because of the enhanced cumulative order quantities. The entire supply chain also benefits from information sharing when \( \phi < \phi_3 \). We can see that \( \phi_3 < \phi_2 \) since the decrement of retailer \( j \)’s expected profit exceeds the increments of retailer \( i \)’s expected profit and the manufacturer’s expected profit in region \((\phi_3, \phi_2)\).

Contrary to the low-demand signal scenario, retailer \( i \)’s expected profit increases with the probability \( \phi \) when observing a high-demand signal. This is because retailer \( i \) will increase his order quantity when forecasting a booming market. A similar action will be adopted by retailer \( j \) after he gets the updated information. As shown in Figure 7(a), \( \pi_i^{TN*} \), \( \pi_i^{TS*} \), and \( \pi_j^{TS*} \) increase with \( \phi \). Figure 7(a) shows that retailer \( i \) can benefit from sharing the high-demand signal when \( \phi < \phi_4 \). The reason is that the benefits of being the first-mover and the higher carbon emission abatement level outweigh the cost of strengthened double marginalization. When \( \phi > \phi_4 \), the wholesale price is very high, which hurts retailer \( i \). We can also see that retailer \( j \) gets hurt from information sharing.
Figure 6: Impacts of $\phi$ on profits with low-demand signal.

Figure 7: Impacts of $\phi$ on profits with high-demand signal.
It implies that obtaining information may not make profit under some conditions.

Figure 7(b) shows that the manufacturer’s expected profit also increases with \( \phi \) under information sharing scenario due to the positive relationship between \( w \) and the updated mean demand \( u_x \). We can also see that the manufacturer always benefits from sharing the high-demand information, which is consistent with Theorem 9(c). As the increment of the manufacturer’s expected profit is larger than the decrements of the retailers’ expected profits, the supply chain performance is improved, as shown in Figure 7(b).

### 7. Conclusions

Under carbon emission regulations, enterprises have to control their carbon emissions in the producing process. In this paper, we investigate how information sharing affects operational decisions under cap-and-trade regulation. The results show that the wholesale price and the carbon emission abatement respond positively to the demand forecast signal. As a result, information sharing results in two effects in a bilateral monopoly supply chain. Thus, the well-informed retailer benefits from low-demand information sharing. However, the well-informed retailer can benefit from high-demand information sharing in a supply chain with competing retailers due to the enhanced carbon emission abatement effect and the weakened competition effect. When competition exists, we find that the uninformed retailer does not always benefit from information sharing. Thus, the uninformed retailer should identify when and what kind of information he is able to accept. For the manufacturer, the impact of information sharing has a correlation with her capability in abating carbon emissions. Thus, firms should make efforts to improve their ability of cleaner production to make profit from information sharing.

There are several possible directions for future study. First, we assume that the members are well-funded. In practice, firms may face financial problems. It might be interesting to discuss the impacts of capital constraints on operational decisions with information asymmetry. Second, the retailers order from a mutual manufacturer. When the competition exists in the upstream firms, should the retailer share information with them sequentially or simultaneously? It might be interesting to investigate the impacts of upstream competition on information sharing and carbon emission reduction. Finally, we assume that only one retailer has superior information. It might be interesting to study the case in which all the members have their own private information.

### Appendix

**Proof of Proposition 1.** In no-information sharing scenario, taking the first and second derivative of \( \pi_i^N \) with respect to \( q_{lx}^N \), we get

\[
\frac{\partial \pi_i^N}{\partial q_{lx}^N} = u_x + be^N - w^N - 2d_{lx}^N, \tag{A.1}
\]

\[
\frac{\partial^2 \pi_i^N}{\partial (q_{lx}^N)^2} = -2. \tag{A.2}
\]

Thus, by solving \( \frac{\partial \pi_i^N}{\partial q_{lx}^N} = 0 \), we get

\[
d_{lx}^N = \frac{1}{2} \left( u_x + be^N - w^N \right). \tag{A.3}
\]

Substituting \( d_{lx}^N \) into \( \pi_m^N \), then, taking the first derivative of \( \pi_m^N \) with respect to \( w^N \) and \( \epsilon^N \), we get

\[
\frac{\partial \pi_m^N}{\partial w^N} = \frac{c + (b - ke_0)\epsilon^N + ke_0 + u - 2w^N}{2}, \tag{A.4}
\]

\[
\frac{\partial \pi_m^N}{\partial \epsilon^N} = -2\tau^N + ke_0 \left( u - w^N \right) + b \left[ w^N + ke_0 \left( 2\epsilon^N - 1 \right) - c \right]. \tag{A.5}
\]

By taking the second derivatives, we get

\[
\frac{\partial^2 \pi_m^N}{\partial (w^N)^2} = -1; \tag{A.6}
\]

\[
\frac{\partial^2 \pi_m^N}{\partial \epsilon^N \partial w^N} = -\tau + bke_0; \tag{A.7}
\]

\[
\frac{\partial^2 \pi_m^N}{\partial \epsilon^N \partial \epsilon^N} = \frac{b - ke_0}{2}. \tag{A.8}
\]

The Hessian matrix of \( \pi_m^N(w^N, \epsilon^N) \) is

\[
H(w^N, \epsilon^N) = \begin{bmatrix}
-1 & \frac{b - ke_0}{2} \\
\frac{b - ke_0}{2} & -\tau + bke_0
\end{bmatrix}. \tag{A.9}
\]

Then, \( \det[H(w^N, \epsilon^N)] = \frac{4\tau - (b + ke_0)^2}{4} > 0 \).

Hence, by solving \( \frac{\partial \pi_m^N}{\partial w^N} = 0 \) and \( \frac{\partial \pi_m^N}{\partial \epsilon^N} = 0 \), we get

\[
e^{N*} = \frac{(b + ke_0)(u - c - ke_0)}{4\tau - (b + ke_0)^2}, \tag{A.10}
\]

\[
w^{N*} = \frac{u \left( 2\tau - k^2e_0 - bke_0 \right) + (2\tau - b^2 - bke_0)(c + ke_0)}{4\tau - (b + ke_0)^2}. \tag{A.11}
\]

Substituting \( e^{N*} \) and \( w^{N*} \) into \( d_{lx}^N \), we get

\[
d_{lx}^{N*} = \frac{u_x}{2} + \frac{[(ke_0 + b)^2 - 2\tau]u - 2\tau(c + ke_0)}{8\tau - 2(b + ke_0)^2}. \tag{A.12}
\]

By solving \( d_{lx}^{N*} > 0 \), we get \( r_i/r > \frac{(2\tau - (b + ke_0)^2)}{4\tau - (b + ke_0)^2} \) or \( r_i/r < \frac{(2\tau - b^2 - bke_0)}{4\tau - (b + ke_0)^2} \) and \( \rho < \frac{(2\tau(1 - r_i) + (r - r_i)(2\tau - (b + ke_0)^2))}{(2\tau - (b + ke_0)^2)[2\tau - (b + ke_0)^2]r - [4\tau - (b + ke_0)^2]r_i}. \)
Proof of Proposition 2. The proof is similar to that of Proposition 1. □

Proof of Theorem 3. When observing a low-demand signal, substituting \( q_{ix}^{N*} \), \( e^{N*} \), and \( w^{N*} \) into \( \pi_{ix}^{N} \) and \( \pi_{m}^{N} \), we get

\[
\pi_{ix}^{N*} = \frac{2 \tau (c + ke_0) + [2 \tau - (b + ke_0)^2] u + [(b + ke_0)^2 - 4 \tau] u_x^2}{4 [(b + ke_0)^2 - 4 \tau]} \quad (A.8)
\]

Then, we find \( \pi_{ix}^{N*} - \pi_{ix}^{N*} > 0 \) and \( \pi_{ix}^{N*} - \pi_{ix}^{N*} < 0 \). Hence, Theorem 3(a) is proved.

In a similar way, we can prove Theorem 3(b). □

Proof of Proposition 4. In the competing setting, taking the first and second derivative of retailer \( j \)'s expected profit \( \pi_{ix}^{TN} \) with respect to \( q_{ix}^{TN} \), we get

\[
\frac{\partial \pi_{ix}^{TN}}{\partial q_{ix}^{TN}} = u_x + b \epsilon - w - q_{ix}^{TN} - 2 q_{ix}^{TN},
\]

\[
\frac{\partial^2 \pi_{ix}^{TN}}{\partial (q_{ix}^{TN})^2} = -2.
\]

Taking the first and second derivative of retailer \( j \)'s expected profit \( \pi_{j}^{TN} \) with respect to \( q_{j}^{TN} \), we get

\[
\frac{\partial \pi_{j}^{TN}}{\partial q_{j}^{TN}} = u + b \epsilon - w - q_{j}^{TN} - 2 q_{j}^{TN},
\]

\[
\frac{\partial^2 \pi_{j}^{TN}}{\partial (q_{j}^{TN})^2} = -2.
\]

As the retailers place orders simultaneously in no-information sharing scenario, by solving \( \partial \pi_{ix}^{TN} / \partial q_{ix}^{TN} = 0 \) and \( \partial \pi_{j}^{TN} / \partial q_{j}^{TN} = 0 \), we get

\[
q_{ix}^{TN} = \frac{3 u_x - u - 2 w + b \epsilon}{6},
\]

\[
q_{j}^{TN} = \frac{u - w + b \epsilon}{3}.
\]

(A.14)

In no-information scenario, the manufacturer’s expected profit is \( \pi_{m}^{TN} \). Taking the first derivative of \( \pi_{m}^{TN} \) with respect to \( w \) and \( \epsilon \), we get

\[
\frac{\partial \pi_{m}^{TN}}{\partial w} = 2 [c + (b - ke_0) \epsilon + ke_0 + u - 2w] / 3 \quad (A.15)
\]

\[
\frac{\partial \pi_{m}^{TN}}{\partial \epsilon} = -3 \tau \epsilon^2 + 2 ke_0 (u - w^N) + 2b [w^N + ke_0 (2x^N - 1) - c] / 3 \quad (A.16)
\]

By taking the second derivatives, we get

\[
\frac{\partial^2 \pi_{m}^{TN}}{\partial w^2} = \frac{4}{3} \quad (A.17)
\]

\[
\frac{\partial^2 \pi_{m}^{TN}}{\partial \epsilon^2} = \frac{-3 \tau + 4 b ke_0}{3} \quad (A.18)
\]

The Hessian matrix of \( \pi_{m}^{TN}(w, \epsilon) \) is

\[
H(w, \epsilon) = \begin{bmatrix}
-4 & 2b - 2ke_0 \\
2b - 2ke_0 & 3
\end{bmatrix}
\]

(A.19)

Hence, det\(H(w, \epsilon)\) = \((12 \tau - 4(b + ke_0)^2)/9 > 0\).

By solving \( \partial \pi_{m}^{TN} / \partial w = 0 \) and \( \partial \pi_{m}^{TN} / \partial \epsilon = 0 \), we get

\[
e^{TN*} = \frac{(b + ke_0) (u - c - ke_0)}{3 \tau - (b + ke_0)^2} \]

\[
u^{TN*} = \frac{u (3 \tau - 2k^2e_0^2 - 2bke_0) + (3 \tau - 2b^2 - 2bke_0) (c + ke_0)}{6 \tau - 3 (b + ke_0)^2} \]

(A.20)

Substituting \( e^{TN*} \) and \( u^{TN*} \) into \( q_{ix}^{TN} \) and \( q_{j}^{TN} \), we get

\[
q_{ix}^{TN*} = \frac{3u_x - u - 2w + b \epsilon}{6} \quad (A.21)
\]

\[
q_{j}^{TN*} = \frac{u - w + b \epsilon}{3} \quad (A.22)
\]

By solving \( q_{ix}^{TN*} > 0 \), we get the conditions \( r_i/r < (2 \tau - (b + ke_0)^2)/(3 \tau - (b + ke_0)^2) \) and \( \rho < \tau/(\tau(2 \tau - (b + ke_0)^2)) \).

□
Proof of Proposition 5. In the information sharing scenario, retailer $j$'s expected profit is $\pi_{jx}^{TS}$, taking the first derivative of $\pi_{jx}^{TS}$ with respect to $q_{jx}^{TS}$, we get
\[
\frac{\partial \pi_{jx}^{TS}}{\partial q_{jx}^{TS}} = E(a | s_x) - q_{jx}^{TS} - 2q_{jx}^{TS} + b - w.
\]
(A.21)

By solving $\partial \pi_{jx}^{TS}/\partial q_{jx}^{TS} = 0$, we can get $q_{jx}^{TS} = (u_x - q_{jx}^{TS} - w + be)/2$. Substituting $q_{jx}^{TS}$ into retailer $i$'s expected profit $\pi_{ix}^{TS}$ and taking the first and second derivative, we get
\[
\frac{\partial \pi_{ix}^{TS}}{\partial q_{jx}^{TS}} = \frac{u_x + be - w - 2q_{jx}^{TS}}{2},
\]
(A.22)
\[
\frac{\partial^2 \pi_{ix}^{TS}}{\partial (q_{jx}^{TS})^2} = -1.
\]

Then, by solving $\partial \pi_{ix}^{TS}/\partial q_{jx}^{TS} = 0$, we get $q_{jx}^{TS} = (u_x - w + be)/2$. Thus, $q_{jx}^{TS} = (u_x - w + be)/2$.

Similar to Proposition 4, we can get
\[
e_x^{TS} = \frac{3 (b + ke_0) (u_x - c - ke_0)}{8 \tau - 3 (b + ke_0)^2},
\]
\[
u_x^{TS} = \frac{u_x (4 \tau - 3b^2 e_0^2 - 3bk e_0) + (4 \tau - 3b^2 - 3bk e_0) (c + ke_0)}{8 \tau - 3 (b + ke_0)^2}.
\]
(A.23)

Substituting $e_x^{TS}$ and $\nu_x^{TS}$ into $q_{jx}^{TS}$ and $q_{ix}^{TS}$, we get
\[
q_{jx}^{TS} = \frac{\tau (u_x - c - ke_0)}{8 \tau - 3 (b + ke_0)^2},
\]
(A.24)
\[
q_{ix}^{TS} = 2q_{jx}^{TS}.
\]

Proof of Proposition 6.

Proof of Proposition 7. The proof is similar to Proposition 6.

Proof of Theorem 8. (a) As $\pi_{jx}^{TS} = \{\tau (c + ke_0) + [2\tau - (b + ke_0)^2] u + [(b + ke_0)^2 - 3\tau] u_i\}/[8\tau - 3 (b + ke_0)^2]$, then,
\[
\pi_{jx}^{TS} - \pi_{jx}^{NS} = \left\{ \frac{\sqrt{\pi} (u_i - c - ke_0)}{8 \tau - 3 (b + ke_0)^2} - \frac{\tau (c + ke_0) + [2\tau - (b + ke_0)^2] u + [(b + ke_0)^2 - 3\tau] u_i}{6 \tau - 2 (b + ke_0)^2} \right\}.
\]

(b) As $\pi_{jx}^{NS} = \{3 \tau (c + ke_0) + [3 \tau - (b + ke_0)^2] u + [9 \tau - 3 (b + ke_0)^2] u_i\}/[3 \tau - (b + ke_0)^2]$, then,
\[
\pi_{jx}^{NS} - \pi_{jx}^{NS} = \left\{ \frac{\sqrt{\pi} (u_i - c - ke_0)}{8 \tau - 3 (b + ke_0)^2} - \frac{\tau (c + ke_0) + [2\tau - (b + ke_0)^2] u + [(b + ke_0)^2 - 3\tau] u_i}{6 \tau - 2 (b + ke_0)^2} \right\}.
\]

On the other hand,
\[
\frac{\tau (c + ke_0) + [2\tau - (b + ke_0)^2] u + [(b + ke_0)^2 - 3\tau] u_i}{6 \tau - 2 (b + ke_0)^2} > 0.
\]
(A.27)

Then, we get $\pi_{jx}^{TS} - \pi_{jx}^{NS} > 0$.
(b) In a similar way, we can prove that \( \pi_{j l}^{TS^{*}} - \pi_{j l}^{NS^{*}} < 0 \).
(c) The manufacturer’s expected profits in different information sharing formats are

\[
\pi_{m}^{TN^{*}} = kG + \frac{\tau (u - c - ke_0)^2}{6\tau - 2 (b + ke_0)^2}, \quad \pi_{m}^{TS^{*}} = kG + \frac{3\tau (u_l - c - ke_0)^2}{16\tau^2 - 6 (b + ke_0)^2}. \tag{A.28}
\]

Comparing \( \pi_{m}^{TN^{*}} \) and \( \pi_{m}^{TS^{*}} \), we find that if \((b + ke_0)^2 < \left[(8\tau^2 - 9r_l^2)/(3r^2 - 3r_l^2)\right] \) and \( \rho < 1 + \left( \left[3(r - r_l)^2(8\tau - 3(b + kg))^2/(3\tau - (b + kg))^2 - 3(b + kg)^2(r - r_l) + 8\tau r - 9r_l^2)/(3(b + kg)^2(r^2 - r_l^2) - 8\tau^2 r + 9r_l^2 \right] \) or \( \rho < 0 < \left[(8\tau^2 - 9r_l^2)/(3r^2 - 3r_l^2)\right] \) \( (b + ke_0)^2, \pi_{m}^{TS^{*}} > \pi_{m}^{TN^{*}} \). Otherwise, \( \pi_{m}^{TS^{*}} < \pi_{m}^{TN^{*}} \).

\[\square\]

**Proof of Theorem 9.** The proof is similar to that of Theorem 8. \[\square\]

**Data Availability**

No data were used to support this study.

**Conflicts of Interest**

The authors declare that they have no conflicts of interest.

**Acknowledgments**

This work was supported by National Natural Science Foundation of China (No. 71671061) and Graduate Innovation Project of Hunan Province (No. 521293398).

**References**


