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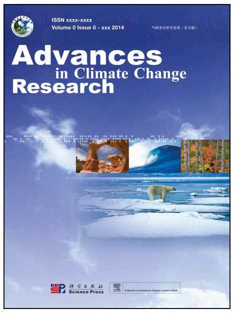

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Downside of a carbon tax for environment: Impact of information sharing

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Abstract: Motivated by the observation that firms invest in carbon emissions reduction to decrease the cost of carbon tax as governments in numerous countries increasingly implement carbon tax to improve the environment, and broad researcher and practitioner agreement that carbon tax implementation always benefits the environment. However, we find that a carbon tax may actually hurt the environment based on a stylized game model with a better-informed retailer (one who controls the demand information sharing with the manufacturer) and a manufacturer. In particular, we find that the carbon emissions reduction may harm the environment if the carbon tax is moderate or both the carbon tax and the demand fluctuation are high. We further reveal free-riding behavior by the retailer, who may enjoy more profit sharing from the supply chain in the presence of carbon emissions reduction. Based on these observations, we argue that a carbon tax does not always benefit the environment when a manufacturer who receives demand information from the retailer responds better to market uncertainty.

Keywords: Supply chain management; Carbon emissions reduction; Carbon tax; Information sharing

1. Introduction

To control carbon emissions, governments in numerous countries including Finland, Sweden, Ireland, Canada, China, and some local governments in the U.S. (e.g., Washington State), have enacted both carbon taxes and environmental laws to protect the environment (Fang et al., 2020; Yu et al., 2020). For example, Canada imposes 15 USD per unit carbon emission, and will improve to 38 USD per unit carbon emission in 2022. However, Australia has abolished the carbon tax since 2014, and insists that carbon tax has a negative effect on the development.

Traditional wisdoms (e.g., Benjaafar et al., 2013; Chen and Hao, 2015; Luo et al., 2016; Turken et al., 2017; Hong et al., 2018) explore the impact of environmental policies like carbon tax, carbon trade, and carbon quota on operational decisions. These studies, however, consider only how firms passively change their operational decisions under environmental policies, with no attention to how they proactively exploit a reply strategy, such as carbon emissions reduction. Hence, Jaber et al. (2013), He et al. (2016), and Yang et al. (2017) not only developed reply strategies like carbon emissions reduction to evaluate the effects of strategy on firm profits but considered the effect of carbon emissions reduction on operational decisions. All these studies assume the retailer and the manufacturer involve in symmetric information.

In practice, downstream retailers often have better information of the market demand than upstream manufacturers. Advances in information technology not only provide retailers with rich product sales data that informs them about market demand (Shang et al., 2016) but allow them to share such information with their suppliers to improve the supply chain's operational efficiency (Chu and Lee, 2006). On the one hand, information sharing reduces the bullwhip effect, which helps supply chain partners build better alliances with each other (Lee et al., 1997); on the other, it enables suppliers to better determine their wholesale prices (Jiang and Hao, 2016). Such information sharing between retailer and supplier is very prevalent in certain industries; for example, the fashion industry's Lands' End and giant retailing chains Costco and Targe, who provide their suppliers with demand (Keifer, 2010) and point-of-sales (POS) data, respectively. Similar practices are common among home improvement, grocery, and electronics firms, although according to Forrester Research (Shang et al., 2016), about 73% of 89 retailers in Europe and North America have no contract to share their POS data with their suppliers. The lack of an incentive to share stems from a double marginalization effect (Li, 2002; Zhang, 2002) that prompts a supplier who receives demand information to raise its wholesale price, thereby sharpening the conflict between supplier and retailer. Following two early studies on supply chain information sharing by Li (2002) and Zhang (2002), research on this topic has become particularly extensive in recent years with a focus on the dual-channel supply chain (Yue and Liu, 2006), confidentiality between partners (Li and Zhang, 2008), production modes (Mishra et al., 2009), inter-chain competition (Ha et al., 2011; Guo et al., 2014a; Shamir and Shin, 2015; Ha et al., 2017), and collaborative new product development (Jha et al., 2017). The above studies focused on retailers share their information with their suppliers whether or not, however, they ignore the role of information sharing on carbon emissions.

Contrary to the conventional wisdoms, the main aim of this study tries to reveal whether carbon tax may hurt environment in supply chains under asymmetric information. We try to examine the effect of carbon emissions reduction on the supply chain and the environment under carbon tax when governments enact carbon tax, and provide governments suggestions for carbon tax. In particular, we seek to answer several related key questions: i) Does a retailer has an incentive to share its information with manufacturer under a carbon tax? ii) Once a retailer has the incentive to share information with the manufacturer, what benefit does information sharing have for the manufacturer, the retailer, the supply chain, consumer surplus, and social welfare? iii) Does a manufacturer actually invest in carbon emissions reduction, and if so, who enjoys more profit sharing from the supply chain than when no carbon emissions reduction occurs? iv) What's effect of carbon tax on the environment?

2. Model

In order to investigate the effect of carbon emissions reduction on the environment in the uncertain market, we consider the scenario in which the manufacturer does not invest in carbon emissions reduction as the benchmark, and then consider the scenario where the manufacturer invests in carbon emissions reduction under the cases of information sharing and no information sharing, respectively. We firstly explore whether the retailer has an incentive to share information with the manufacturer. The retailer shares information only if it benefits from information sharing. Then we examine the effect of carbon emissions reduction on bargaining power between supply chain members and the environment in the uncertain market. More specifically, the improved bargaining allows the retailer more profit sharing from the supply chain, and larger amount of carbon emission hurts the environment. Next, we give the demand functions and the information structure.

2.1 Demand function

The supply chain (*S*) in our model consists of an upstream manufacturer (*M*) who produces a product and sells it at a wholesale price w to a downstream retailer (*R*). The retailer then sells the product at a retail price p to consumers. The consumer demand function (*q*) is uncertain and modeled which is widely adopted by Li (2002) and Zhang (2002) as

$$q(p) = a + \varepsilon - p \tag{1}$$

where $a > 0$ is the market base and ε is a stochastic variable with zero mean and a variance σ^2, with a larger σ^2 representing larger fluctuations in demand.

2.2 Information structure

Similar to the current information sharing literature, we assume that the retailer can acquire a demand signal Y, which is an unbiased estimator of ε; that is, $E\left[Y \middle| \varepsilon\right] = \varepsilon$. This signal is private information to the retailer, who can decide whether or not to share it with the manufacturer. We further assume that the expectation of ε conditional on the signal Y is a linear function of the signal. The structure includes several prior-posterior distribution pairs, including normal-normal, beta-binomial, and gamma-Poisson. Once the signal accuracy is defined as $t = 1 \big/ E\left[Var\left[Y \middle| \varepsilon\right]\right]$, then, based on Ericson (1969),

$$E\left[\varepsilon \middle| Y\right] = \frac{t\sigma^2}{1+t\sigma^2} Y, E\left[\left(E\left[\varepsilon \middle| Y\right]\right)^2\right] = \frac{t\sigma^4}{1+t\sigma^2}.$$

We use β to denote the carbon emissions unit of producing one product before the manufacturer invests in carbon emissions reduction. The manufacturer incurs a cost of carbon tax $\beta\tau$ per unit product, with τ representing the unit carbon tax charged by the government. After the manufacturer invests in carbon reduction, the unit carbon emissions is reduced to $\beta-\delta$, where δ is the carbon emissions reduction. The carbon emissions reduction cost for the manufacturer is then $K\delta^2$, where a smaller K represents the higher carbon emissions reduction efficiency at the same carbon emissions reduction. The quadratic cost function that characterizes the diminishing return of carbon emissions reduction (Ha et al., 2017). In order to guarantee positive demand and carbon emissions reduction below the initial unit carbon emissions like Ha et al. (2017), we assume that $a \geq \beta\sqrt{6K} \geq \beta\tau$. The similar assumption is commonly made in the operations management literature (cf. Li and Zhang, 2008; Ha et al. 2017). This latter, like the linear consumer demand function (cf. Savaskan et al., 2004) and linear information structure (cf. Li, 2002; Zhang, 2002; Shang et al., 2016; Ha et al., 2017) used above, is extensively adopted across the supply chain management literature. To avoid mathematic complexity, both the manufacturer’s unit production cost and the retailer’s retail cost are assumed to be zero, although our main results still hold even when these costs are set to fixed parameters. Different from the conventional wisdoms (cf. Li, 2002; Zhang, 2002; Shang et al., 2016; Ha et al., 2017) on information sharing, we consider the case where manufacturers invests R&D in carbon emissions reduction.

As in most supply chain management studies, we assume that the manufacturer and the retailer are profit-maximizing and risk-neutral decision makers. We also assume that all information except for the demand signal Y is common knowledge for both the manufacturer and the retailer. The time line of the game is displayed in Fig. 1. The manufacturer first decides whether or not to invest in carbon emissions reduction, before which the retailer decides whether or not to share demand forecast information with the manufacturer. The manufacturer then determines the wholesale price to the retailer and the carbon emissions reduction level if this latter is to invest in carbon emissions reduction. Finally, the retailer sets the retail price based on the demand forecast information.

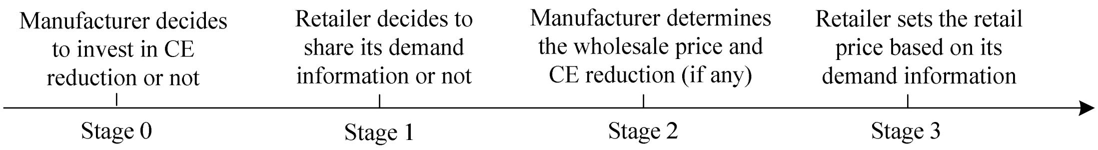


Fig. 1. The time line of the game

3. Results

3.1Benchmark model (B): no carbon emissions reduction

This section analyzes the benchmark model without carbon emissions reduction under two cases: no information sharing and information sharing. Under the former, because the manufacturer receives no demand information from the retailer, the expected profit functions for the manufacturer and retailer are

$$\Pi_{\mathrm{MNI}}^{\mathrm{B}} = E\left[\left(w-\beta\tau\right)q\right], \tag{2}$$

$$\Pi_{\mathrm{RNI}}^{\mathrm{B}} = \left(p-w\right)\left(a+E\left[\varepsilon\middle|Y\right]-p\right). \tag{3}$$

Where $\Pi_{\mathrm{kNI}}^{\mathrm{B}}\left(k=\mathrm{R,M,S}\right)$ denote the ex ante profit of k under no information sharing in Model B. We use standard backward induction to solve the Stackelberg game by first solving the retailer's problem, and then substituting parameters accordingly and solving the manufacturer's problem. The following lemma gives the equilibrium under no information sharing and explores the effect of demand signal on the optimal decisions：

Lemma 1. In Model B, with no information sharing, the manufacturer's optimal wholesale price is

$$w_{\mathrm{NI}}^{\mathrm{B}} = \frac{a+\beta\tau}{2}.$$

The retailer's optimal retail price is

$$p_{\mathrm{NI}}^{\mathrm{B}} = \frac{3a+2E\left[\varepsilon\middle|Y\right]+\beta\tau}{4}.$$

Intuitively from Lemma 1, whereas the optimal retail price is relevant to the demand signal, the optimal wholesale price is unrelated because the manufacturer receives no demand signal from the retailer. Given the optimal decisions, we can compute the ex ante profits of the manufacturer, retailer, and supply chain in the absence of information sharing (let $\Pi_{\mathrm{kNI}}^{\mathrm{B}}\left(k=\mathrm{R},\mathrm{M},\mathrm{S}\right)$ denote the ex ante profit of k under no information sharing in Model B):

$$\Pi_{\mathrm{MNI}}^{\mathrm{B}}=\frac{\left(a-\beta\tau\right)^2}{8}, \tag{4}$$

$$\Pi_{\mathrm{RNI}}^{\mathrm{B}}=\frac{\left(a-\beta\tau\right)^2}{16}+\frac{t\sigma^4}{4\left(1+t\sigma^2\right)}, \tag{5}$$

$$\Pi_{\mathrm{SNI}}^{\mathrm{B}}=\frac{3\left(a-\beta\tau\right)^2}{16}+\frac{t\sigma^4}{4\left(1+t\sigma^2\right)}. \tag{6}$$

In the presence of information sharing, in contrast, the manufacturer does receive demand information from the retailer and can determine the wholesale price based on the demand signal. Then, the profit functions for the manufacturer and retailer are

$$\Pi_{\mathrm{MIS}}^{\mathrm{B}}=E\left[\left(w-\beta\tau\right)q\middle|Y\right], \tag{7}$$

$$\Pi_{\mathrm{RIS}}^{\mathrm{B}}=\left(p-w\right)\left(a+E\left[\varepsilon\middle|Y\right]-p\right). \tag{8}$$

Using a method similar to that for Lemma 1, we obtain the following equilibrium under information sharing:

Lemma 2. In Model B, with information sharing, the manufacturer's optimal wholesale price is

$$w_{\mathrm{IS}}^{\mathrm{B}}=\frac{a+E\left[\varepsilon\middle|Y\right]+\beta\tau}{2}.$$

The retailer's optimal retail price is

$$p_{\mathrm{IS}}^{\mathrm{B}}=\frac{3\left(a+E\left[\varepsilon\middle|Y\right]\right)+\beta\tau}{4}.$$

This latter differs from Lemma 1 in that with information sharing, the optimal wholesale price is related to the demand signal acquired by the manufacturer from the retailer. We also know from Lemmas 1 and 2 that the manufacturer increases the wholesale price based on this demand signal Y after receiving the information from the retailer. Given the optimal decisions in Lemma 2, we can derive the ex ante profits of the manufacturer, retailer, and supply chain in the presence of information sharing (let $\Pi_{\mathrm{kIS}}^{\mathrm{B}}\left(k=\mathrm{M},\mathrm{R},\mathrm{S}\right)$ denote the ex ante profit of k under information sharing in Model B):

$$\Pi_{\mathrm{MIS}}^{\mathrm{B}}=\frac{t\sigma^4}{8\left(1+t\sigma^2\right)}+\frac{\left(a-\beta\tau\right)^2}{8}, \tag{9}$$

$$\Pi_{\mathrm{RIS}}^{\mathrm{B}}=\frac{t\sigma^4}{16\left(1+t\sigma^2\right)}+\frac{\left(a-\beta\tau\right)^2}{16}, \tag{10}$$

$$\Pi_{\mathrm{SIS}}^{\mathrm{B}}=\frac{3t\sigma^4}{16\left(1+t\sigma^2\right)}+\frac{3\left(a-\beta\tau\right)^2}{16}. \tag{11}$$

Based on the manufacturer, retailer, and supply chain ex ante profits in Eq. (4−6) and Eq. (9−11), we can explore the information sharing decision of the retailer and investigate its effects on the manufacturer and supply chain. The result is summarized in Proposition 1.

Proposition 1. In Model B, information sharing hurts both the retailer and the supply chain but benefits the manufacturer.

Proposition 1, whose underlying rationale is that information sharing allows the manufacturer to determine its wholesale price more precisely, is consistent with the extant literature on information sharing in supply chains (e.g., Li and Zhang, 2008; Ha et al., 2011). Based on this information, however, the manufacturer increases the wholesale price, which sharpens the double marginalization effect and prevents the retailer from benefiting from information sharing. As a result, more pronounced double marginalization problem not only hurts the retailer but also harms the supply chain in the communicative supply chain. This implies when the manufacturer does not invest in carbon emissions reduction, the retailer has no incentives to share demand information with the manufacturer, which is consistent with the literature about information sharing (Yue and Liu, 2006; Ha et al., 2011).

3.2.Model C: with carbon emissions reduction

When we analyze the model with carbon emissions reduction under the same two cases of no information sharing and information sharing, the expected profit functions of the manufacturer and retailer under the former are

$$\Pi_{\mathrm{MNI}}^{\mathrm{C}} = E\Big[\big(w - (\beta - \delta)\tau\big)q - K\delta^{2}\Big], \tag{12}$$

$$\Pi_{\mathrm{RNI}}^{\mathrm{C}} = (p - w)\big(a + E[\varepsilon|Y] - p\big), \tag{13}$$

and the equilibrium is as summarized in Lemma 3.

Lemma 3. In Model C, with no information sharing, the manufacturer's optimal wholesale price and carbon reduction level are

$$w_{\mathrm{NI}}^{\mathrm{C}} = \frac{a\left(4K - \tau^{2}\right) + 4K\beta\tau}{8K - \tau^{2}}, \quad \delta_{\mathrm{NI}}^{\mathrm{C}} = \frac{(a - \beta\tau)\beta\tau}{8K - \tau^{2}}.$$

The retailer's optimal retail price is

$$p_{\mathrm{NI}}^{\mathrm{C}} = \frac{1}{2}\big(a + E[\varepsilon|Y]\big) + \frac{a\left(4K - \tau^{2}\right) + 4K\beta\tau}{2\left(8K - \tau^{2}\right)}.$$

Intuitively, under this condition of no information sharing, the carbon reduction level is unrelated to the demand signal received by the manufacturer from the retailer. Let $\Pi_{\mathrm{kNI}}^{\mathrm{C}}\left(k = \mathrm{R}, \mathrm{M}, \mathrm{S}\right)$ denote the ex ante profit of k under no information sharing in Model C. Then, based on Lemma 3, we can compute the ex ante profits for the manufacturer, retailer, and supply chain when the manufacturer invests in carbon emissions reduction but no information is shared:

$$\Pi_{\mathrm{MNI}}^{\mathrm{C}} = \frac{K(a - \beta\tau)^{2}}{8K - \tau^{2}}, \tag{14}$$

$$\Pi_{\mathrm{RNI}}^{\mathrm{C}} = \frac{1}{4}\frac{t\sigma^{4}}{\left(1 + t\sigma^{2}\right)} + \frac{4K^{2}(a - \beta\tau)^{2}}{\left(8K - \tau^{2}\right)^{2}}, \tag{15}$$

$$\Pi_{\mathrm{SNI}}^{\mathrm{C}} = \frac{1}{4}\frac{t\sigma^{4}}{\left(1 + t\sigma^{2}\right)} + \frac{K(a - \beta\tau)^{2}\left(12K - \tau^{2}\right)}{\left(8K - \tau^{2}\right)^{2}}. \tag{16}$$

On receiving the demand information from the retailer, the manufacturer can make its decisions based on the demand signal. The manufacturer and retailer profit functions are then

$$\Pi_{\mathrm{MIS}}^{\mathrm{C}} = E\left[\left(w-\tau\left(\beta-\delta\right)\right)q-K\delta^2\middle|Y\right], \tag{17}$$

$$\Pi_{\mathrm{RIS}}^{\mathrm{C}} = \left(p-w\right)\left(a+E\left[\varepsilon\middle|Y\right]-p\right). \tag{18}$$

The equilibrium under information sharing is summarized in Lemma 4.

Lemma 4. In Model C, with information sharing, the manufacturer's optimal wholesale price and carbon reduction level are

$$w_{\mathrm{IS}}^{\mathrm{C}} = \frac{\left(a+E\left[\varepsilon|Y\right]\right)\left(4K-\tau^2\right)+4K\beta\tau}{8K-\tau^2}, \quad \delta_{\mathrm{IS}}^{\mathrm{C}} = \frac{\left(a+E\left[\varepsilon|Y\right]-\beta\tau\right)\tau}{8K-\tau^2}.$$

The retailer's optimal retail price is

$$p_{\mathrm{IS}}^{\mathrm{C}} = \frac{\left(a+E\left[\varepsilon|Y\right]\right)\left(6K-\tau^2\right)+2K\beta\tau}{8K-\tau^2}.$$

According to Lemma 4, the optimal carbon emissions reduction level increases with the demand signal acquired by the manufacturer from the retailer. Lemma 4 also shows that when the carbon tax is low, i.e., $\tau \le 2\sqrt{K}$, the wholesale price increases with the demand signal. When the carbon tax is high, i.e., $2\sqrt{K} < \tau < \sqrt{6K}$, however, the wholesale price decreases with the demand signal. On the one hand, the manufacturer always improves the wholesale price which makes the double marginalization problem more significant with no carbon emissions. On the other hand, the value of carbon emissions reduction is more in larger Y which induces much higher demand. Intuitively, this result hinges on the tradeoff between the double marginalization effect and the carbon emissions reduction benefit with manufacturer investing in the carbon emissions. That is, when the carbon tax is low, the double marginalization effect dominates the carbon emissions reduction benefit, so the manufacturer is better off because of the increased wholesale price. When the carbon tax is high, however, the carbon emissions reduction benefit dominates the double marginalization effect, so the manufacturer is better off because of the decreased wholesale price.

Let $\Pi_{\mathrm{kIS}}^{\mathrm{C}}\left(k=\mathrm{R},\mathrm{M},\mathrm{S}\right)$ denote the ex ante profit of k under information sharing in Model C. Then, based on Lemma 4, the ex ante profits for the manufacturer, the retailer, and the supply chain under information sharing can be expressed as follows:

$$\Pi_{\mathrm{MIS}}^{\mathrm{C}}=\frac{K}{8K-\tau^2}\left[\left(a-\beta\tau\right)^2+\frac{t\sigma^4}{\left(1+t\sigma^2\right)}\right], \tag{19}$$

$$\Pi_{\mathrm{RIS}}^{\mathrm{C}}=\frac{4K^2}{\left(8K-\tau^2\right)^2}\left[\left(a-\beta\tau\right)^2+\frac{t\sigma^4}{\left(1+t\sigma^2\right)}\right], \tag{20}$$

$$\Pi_{\mathrm{SIS}}^{\mathrm{C}}=\frac{K\left(12K-\tau^2\right)}{\left(8K-\tau^2\right)^2}\left[\left(a-\beta\tau\right)^2+\frac{t\sigma^4}{\left(1+t\sigma^2\right)}\right], \tag{21}$$

Next we need to answer the first key question, namely, whether the retailer has an incentive to share the demand information with the manufacturer. In particular, if information sharing benefits the retailer, we can say that the retailer has an incentive to share the demand information; otherwise, the retailer has no incentives to share the demand information. And from these results in Eq. (14−16) and Eq. (19−21), we obtain Proposition 2.

Proposition 2. In Model C,

(i) information sharing always benefits the manufacturer;

(ii) information sharing hurts the retailer if $0\le\tau\le 2\sqrt{K}$ but benefits the retailer if $2\sqrt{K}<\tau<\sqrt{6K}$;

(iii) information sharing hurts the supply chain if $0\le\tau\le\sqrt{\left(6-2\sqrt{5}\right)K}$ but benefits the supply chain if $\sqrt{\left(6-2\sqrt{5}\right)K}<\tau<\sqrt{6K}$.

Proposition 2 confirms that, as in Proposition 1 for the benchmark model, the manufacturer always benefits from information sharing because the demand information helps it to precisely determine the wholesale price and carbon reduction level. Proposition 2 also suggests that whether information sharing will hurt or benefit the retailer depends on the level of carbon tax. That is, intuitively, the outcome depends on the tradeoff between the double marginalization effect and the carbon emissions reduction benefit. When the carbon tax is low, the double marginalization effect dominates the carbon emissions reduction benefit, so the retailer is worse off under information sharing than under no information sharing because of the increase in wholesale price. When the carbon tax is large, however, the carbon emissions reduction benefit dominates the double marginalization effect, so the retailer is better off because of the decrease in wholesale price.

To illustrate the results more clearly, we consider a scenario in which the carbon tax is sufficiently high. Intuitively, the optimal strategy for the manufacturer is to invest more in carbon emissions reduction and determine a low wholesale price so that more consumers will purchase the product. The manufacturer chooses this strategy under information sharing but not under no information sharing. On the other hand, when the carbon tax is sufficiently low, the manufacturer's optimal strategy is to invest less in carbon emissions reduction and set a high wholesale price. Under information sharing, however, the manufacturer sets a low wholesale price.

Proposition 2 further shows that, contrary to the findings of Li and Zhang (2008) and Ha et al. (2011), information sharing can create a win-win outcome for both the manufacturer and the retailer when the carbon tax is high, i.e., $\tau > 2\sqrt{K}$. It also reveals that information sharing is more likely to increase the supply chain's profit than the retailer's (with a threshold value of $\sqrt{\left(6-2\sqrt{5}\right)K} \approx 1.24\sqrt{K}$, which is smaller than the threshold value of $2\sqrt{K}$). Thus, when $\sqrt{\left(6-2\sqrt{5}\right)K} \le \tau \le 2\sqrt{K}$, both the manufacturer and the supply chain are better off because of information sharing. In this case, the manufacturer can obtain demand information by paying the retailer fee; however, when $\tau < \sqrt{\left(6-2\sqrt{5}\right)K}$, only the manufacturer is better off because the decrease in supply chain profit prevents information sharing.

Whereas the analysis so far has explored the effects of information sharing on the manufacturer, the retailer and the supply chain, we now analyze its effect on consumer surplus and social welfare. Because the demand signal that is part of our model's production quantities is a stochastic variable, we compute these two factors using an expectation value.

More specifically, following He et al. (2016), we use Lemmas 3 and 4 to compute the expected consumer surplus under conditions of no information sharing and information sharing:

$$CS_{\mathrm{NI}}^{\mathrm{C}} = E\left[\frac{1}{2}\left(a+\varepsilon-p_{NI}^{C}\right)^{2}\right] = \frac{1}{8}\frac{t\sigma^{4}}{\left(1+t\sigma^{2}\right)} + \frac{2K^{2}\left(a-\beta\tau\right)^{2}}{\left(8K-\tau^{2}\right)^{2}}, \tag{22}$$

$$CS_{\mathrm{IS}}^{\mathrm{C}} = E\left[\frac{1}{2}\left(a+\varepsilon-p_{IS}^{C}\right)^{2}\right] = \frac{2K^{2}}{\left(8K-\tau^{2}\right)^{2}}\left[\left(a-\beta\tau\right)^{2} + \frac{t\sigma^{4}}{\left(1+t\sigma^{2}\right)}\right]. \tag{23}$$

Similarly, because social welfare generally consists of the manufacturer's profit, the retailer's profit, and consumer surplus (He et al., 2016), we can use Lemmas 3−4 and Eq. (22−23) to compute social welfare without and with information sharing:

$$SW_{\mathrm{NI}}^{\mathrm{C}} = \Pi_{\mathrm{SNI}}^{\mathrm{C}} + CS_{\mathrm{NI}}^{\mathrm{C}} = \frac{3t\sigma^{4}}{8\left(1+t\sigma^{2}\right)} + \frac{K\left(14K-\tau^{2}\right)\left(a-\beta\tau\right)^{2}}{\left(8K-\tau^{2}\right)^{2}}, \tag{24}$$

$$SW_{\mathrm{IS}}^{\mathrm{C}} = \Pi_{\mathrm{SIS}}^{\mathrm{C}} + CS_{\mathrm{IS}}^{\mathrm{C}} = \frac{K\left(14K-\tau^{2}\right)}{\left(8K-\tau^{2}\right)^{2}}\left[\left(a-\beta\tau\right)^{2} + \frac{t\sigma^{4}}{\left(1+t\sigma^{2}\right)}\right]. \tag{25}$$

Then, based on Eq. (22−25), we can explore the effects of information sharing on both consumer surplus and social welfare, and summarize the results in Proposition 3:

Proposition 3. When the manufacturer invests in carbon emissions reduction,

(i) information sharing benefits consumer surplus if $2\sqrt{K} < \tau < \sqrt{6K}$ but hurts consumer surplus if $0 \le \tau \le 2\sqrt{K}$;

(ii) information sharing benefits social welfare if

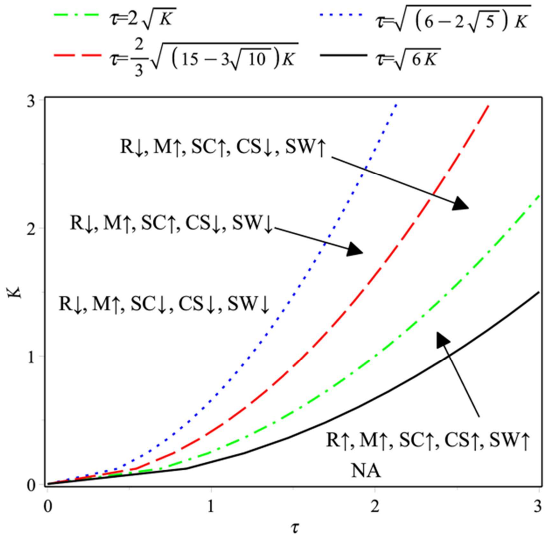
$$\frac{2}{3}\sqrt{\left(15-3\sqrt{10}\right)K} < \tau < \sqrt{6K},$$

but hurts social welfare if

$$0 \le \tau \le \frac{2}{3}\sqrt{\left(15-3\sqrt{10}\right)K} \approx 1.57\sqrt{K}.$$

Traditionally, high taxes are widely recognized to harm consumer surplus through increased retail prices (Marshall, 1982), but interestingly, Proposition 3 finds that a high carbon tax may benefit consumer surplus. This can intuitively be attributed to information sharing between the manufacturer and retailer weakening the double marginalization effect when the manufacturer may decrease the wholesale price. This latter induces the retailer to reduce the retail price, which benefits the consumer surplus. Proposition 3 also reveals that although information sharing affects the consumer surplus for the retailer (as shown in Proposition 2), when the carbon tax is low, $0 \le \tau \le 2\sqrt{K}$, this effect is converse to that for the manufacturer because the low carbon tax plays a minimal role in reducing the manufacturer's carbon emissions. In fact, this latter induces the manufacturer to increase the wholesale price, which hurts the consumer surplus. Proposition 3 thus further reveals that, from a social planning perspective, information sharing has a similar effect on social welfare as on consumer surplus in that a high carbon tax weakens the double marginalization effect.

Whereas Propositions 2 and 3 together underscore the differences in information sharing preferences among the different players, by summarizing the main findings in Fig. 2 with $\beta=1$, we show that although retailer, manufacturer, supply chain, consumer surplus, and social welfare preferences in most regions differ, in one region, all players' benefits are consistent when carbon tax is sufficiently high. More specially, $x_{\mathrm{IS}}^{\mathrm{C}} - x_{\mathrm{NI}}^{\mathrm{C}} > 0$ ($x = \mathrm{R}, \mathrm{M}, \mathrm{SC}, \mathrm{CS}, \mathrm{SW}$) means that the retailer's profit, the manufacturer's profit, the supply chain profit, the consumer surplus, and the social welfare increase with carbon emissions reduction, respectively; otherwise, this means the profit, the consumer surplus, and the social welfare decrease. This observation indicates that information sharing has the ability to coordinate the preferences of all players. We also note that the coordinated region diminishes as the carbon emissions reduction cost parameter increases and even vanishes when it becomes relatively hard to raise the carbon emissions reduction level. In this case, the manufacturer does not want to invest more in carbon emissions reduction and increases the wholesale price to cover its cost, which sharpens the double marginalization effect. When the carbon tax is not sufficiently high, however, although information sharing benefits the manufacturer and may benefit the supply chain and social welfare, it always harms the retailer and consumer surplus.



Note: $x\uparrow(\downarrow), x = \mathrm{R}, \mathrm{M}, \mathrm{SC}, \mathrm{CS}, \mathrm{SW}$ denotes $x_{\mathrm{IS}}^{\mathrm{C}} - x_{\mathrm{NI}}^{\mathrm{C}} > 0(< 0)$

Fig. 2. Summary of information sharing's effects on retailer (R), manufacturer (M), supply chain (SC), consumer surplus (CS) and social welfare (SW).

4. Effects of carbon emissions reduction

Having characterized the retailer's information sharing strategy and investigated its effect on the manufacturer, supply chain, consumer surplus, and social welfare, we now evaluate the effect of carbon emissions reduction on the manufacturer and retailer, and compare it to that when carbon emissions reduction is absent. Using the simple evaluation criterion of comparing each player's profits under no carbon emissions reduction versus carbon emissions reduction, we show not only that carbon emissions reduction always benefits the manufacturer but that it also benefits the retailer (see the proof of Proposition 4). This finding indicates free-riding behavior by the retailer when the manufacturer invests in carbon emissions reduction. That is, the manufacturer reduces the carbon emissions tax cost to increase profits, which also induces it to lower the wholesale price. As a result, the retailer profit increases more than in the case of no carbon emissions reduction.

Nevertheless, even though both the manufacturer and the retailer benefit from carbon emissions reduction, it is still unclear who gains more profit sharing from the supply chain relative to the case of no carbon emissions reduction. Letting $\rho_{\mathrm{RNI}}^{\mathrm{B}}$ denote retailer profit sharing in Model B with no information sharing and $\rho_{\mathrm{RNI}}^{\mathrm{C}}\left(\rho_{\mathrm{RIS}}^{\mathrm{C}}\right)$ denote it in Model C with no information sharing (information sharing), then,

$$\rho_{\mathrm{RNI}}^{\mathrm{B}}=\frac{(a-\beta\tau)^2+4T}{3(a-\beta\tau)^2+4T},\ \rho_{\mathrm{RIS}}^{\mathrm{C}}=\frac{4K}{12K-\tau^2},$$

$$\rho_{\mathrm{RNI}}^{\mathrm{C}}=\frac{\left(8K-\tau^2\right)^2 T+16K^2(a-\beta\tau)^2}{\left(8K-\tau^2\right)^2 T+4K\left(12K-\tau^2\right)(a-\beta\tau)^2},$$

where $T=t\delta^4\big/\left(1+t\delta^2\right)$. Based on these results, the following proposition summarizes our main finding.

Proposition 4. Relative to the case of no carbon emissions reduction, the retailer gains more profit sharing from the supply chain under carbon emissions reduction. That is $\rho_{\mathrm{RNI}}^{\mathrm{C}}>\rho_{\mathrm{RNI}}^{\mathrm{B}}$ if $T\le T_1$ and $0\le\tau\le 2\sqrt{K}$; $\rho_{\mathrm{RIS}}^{\mathrm{C}}>\rho_{\mathrm{RNI}}^{\mathrm{B}}$ if $T\le T_2$ and $2\sqrt{K}<\tau<\sqrt{6K}$, where

$$T=\frac{t\delta^4}{1+t\delta^2},\ T_1=\frac{2K(a-\beta\tau)^2}{8K-\tau^2}\ \text{ and }\ T_2=\frac{\tau^2(a-\beta\tau)^2}{4\left(8K-\tau^2\right)}.$$

We depict the results of Proposition 4 in Fig. 3, where $a=5,\beta=1,K=2$. Although it is well known that the manufacturer gains more profit sharing than the retailer under carbon emissions reduction than under no carbon emissions reduction, the results reveal that the retailer may gain more profit sharing from the supply chain when the fluctuation in demand is relatively small (i.e., when T is an increasing function in σ^2). The rationale for this outcome is that following carbon emissions reduction, the retailer enjoys a cost reduction in wholesale price that the manufacturer does not receive. As a result, the retailer may obtain more profit sharing from the supply chain after the manufacturer invests in carbon emissions reduction. When the demand fluctuation is sufficiently large, in contrast, the cost reduction advantage is insufficient to cover the disadvantage of tremendous demand fluctuation. Hence, the retailer cannot obtain more profit sharing from the supply chain. To illustrate, we consider a special case of infinite demand fluctuation, $\sigma^2 \to \infty$, in which the manufacturer invests more in carbon emissions reduction and increases the wholesale price. This latter reduces the retailer's profit margin and reduces its profit sharing from the supply chain. In other words, the carbon emissions reduction improves the manufacturer's bargaining with the better-informed retailer.

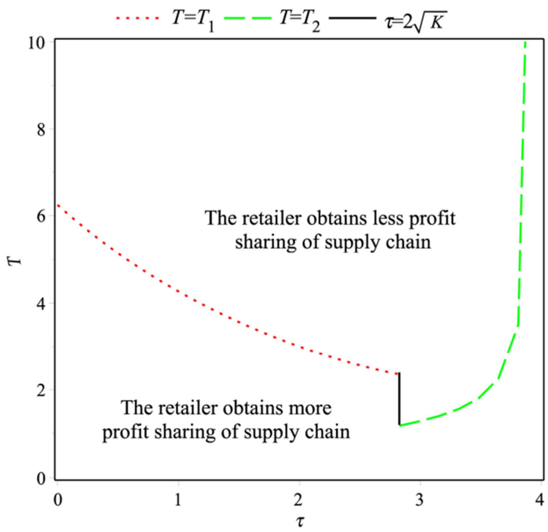


Fig. 3. Illustration of the Proposition 4 results

The carbon emissions is closely relative with the carbon tax. To help the government set the carbon tax to reduce the carbon emissions better which improves the environment, we should evaluate the environmental impact after the manufacturer invests in carbon emissions reduction. Because the optimal quantities are stochastic about the demand signal Y, we define environmental impact in terms of ex ante value. Letting $EI_{\mathrm{NI}}^{\mathrm{B}}$ denote the environmental impact in Model B and using $EI_{\mathrm{NI}}^{\mathrm{C}}$ and $EI_{\mathrm{IS}}^{\mathrm{C}}$ to denote it in Model C under both no information sharing and information sharing, then

$$EI_{\mathrm{NI}}^{\mathrm{B}}=E\left[\zeta\beta q_{\mathrm{NI}}^{\mathrm{B}}\right]=\frac{\zeta\beta(a-\beta\tau)}{4},$$

$$EI_{\mathrm{NI}}^{\mathrm{C}}=E\left[\zeta\left(\beta-\delta_{\mathrm{NI}}^{\mathrm{C}}\right)q_{\mathrm{NI}}^{\mathrm{C}}\right]=\frac{4\zeta K(a-\beta\tau)(8K-a\beta\tau)}{2\left(8K-\tau^{2}\right)^{2}},$$

$$EI_{\mathrm{IS}}^{\mathrm{C}}=E\left[\zeta\left(\beta-\delta_{\mathrm{IS}}^{\mathrm{C}}\right)q_{\mathrm{IS}}^{\mathrm{C}}\right]=-\frac{2\zeta\tau K}{\left(8K-\tau^{2}\right)^{2}}T+\frac{2\zeta K(a-\beta\tau)(8K-a\beta\tau)}{\left(8K-\tau^{2}\right)^{2}},$$

where ζ is the unit environmental impact. Without loss of generality, we set $\zeta=1$, and based on the above results, derive the following proposition:

Proposition 5. Compared to the case of no carbon emissions reduction, there exists a threshold value of τ^*, the unique root of $f(\tau)=\beta\tau\left(16K-\tau^2\right)-8aK=0$ in $\left[0,2\sqrt{K}\right]$, at which carbon emissions reduction benefits the environment if (i) $0\le\tau\le\tau^*$ or (ii) $T<T_3$ and $2\sqrt{K}<\tau<\sqrt{6K}$, where

$$T_3=\frac{(a-\beta\tau)\left(\beta\tau\left(16K-\tau^2\right)-8aK\right)}{8K}.$$

Conversely, carbon emissions reduction harms the environment if

(i) $\tau^*<\tau\le 2\sqrt{K}$ or (ii) $T\ge T_3$ and $2\sqrt{K}<\tau<\sqrt{6K}$.

Proposition 5 helps the government to better design carbon tax policy. One can expect that the carbon emissions reduction always has positive impacts on the environment under carbon tax, practically this is not true. In particular, the carbon emissions reduction may harm the environment if the carbon tax is moderate or both the carbon tax and the demand fluctuation are high, as illustrated in Fig. 4, where $a=5,\beta=1,K=3$. The intuition can be explained as follows. The amount of carbon emission is comprised of the unit carbon emission and the demand, and larger demand leads to a larger amount of carbon emission, which harms the environment. According to the Fig. 4, when the carbon tax is high, as Proposition 2 shows, the carbon emissions reduction benefits dominate the double marginalization effect, namely, decrease in wholesale price weakens the double marginalization effect. In response, the retailer reduces its retail price, which increases demand. As a result, the amount of carbon emission is larger when the manufacturer invests in carbon emissions reduction, which harms the environment. Nevertheless, Fig. 4 further indicates that a large T equals a large demand fluctuation σ^2, which induces the manufacturer to increase its wholesale price and then the retailer to improve its retail price, thereby decrease demand. As a result, when both the carbon tax and the demand fluctuation are high, the carbon emissions reduction makes the environment better off.

On the other hand, this study adds significant insights to the extant literature by revealing the possible negative impacts of carbon tax on the environment. Traditionally, studies have tended to argue that carbon tax is either good for the environment (Jin, 2014; Bouchery et al., 2012; Floros and Vlanchou, 2005) or has no significant impact on it (Lin and Li, 2011; Bruvoll and Larsen, 2004). Recent work by Li et al. (2015), however, finds that a carbon tax might have a contingent effect (i.e., either good or not significant) on the environment under different conditions. Nevertheless, very few studies recognize that, in some cases, the environment may be worse off because of a carbon tax.

This study also extends the literature on carbon tax by showing that it is a moderate carbon tax that might undermine the environment. Yet, current research offers no widely accepted criteria for classifying low, moderate, and high carbon taxes, meaning that different studies employ different classification criteria (e.g., Zhang et al., 2016; Li et al., 2015; Guo et al., 2014b). This lack of accepted standard is one reason why our study findings refute those of Guo et al (2014b), who argue that a moderate carbon tax can effectively protect the environment. In fact, Guo et al (2014b) only provide a subjective definition of a moderate carbon tax in the Chinese market context without justifying its rationale or citing official government criteria. Nor do they explain the comparability and applicability of their classification standard in other countries. For example, when the purchasing power parity of different currencies is taken into account, a moderate carbon tax in China might be a low or high tax in other countries, which reduces the validity of their conclusions. With our Proposition 5, in contrast, we formally demonstrate the need for government policy design to consider the potentially negative impacts of a carbon tax to the environment.

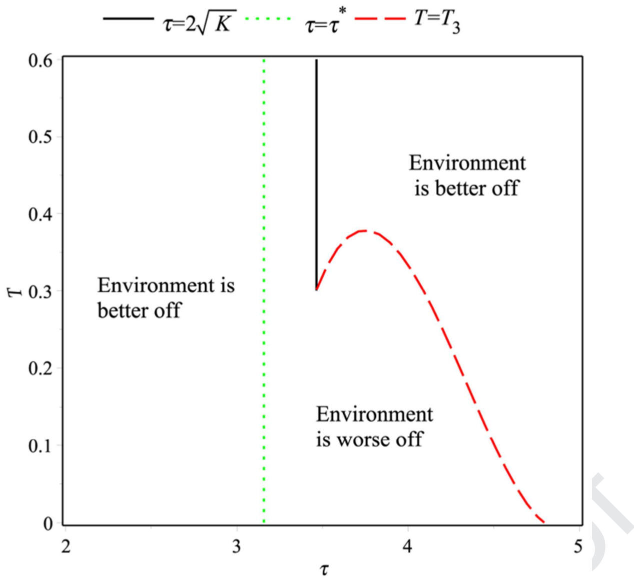


Fig.4. Illustration of Proposition 5

5. Managerial insights and suggestions for carbon tax

Nowadays, as the governments, such as Finland, Sweden, Ireland, China and Canada, increasingly enact carbon tax in order to reduce carbon emissions, manufacturers not only passively change their operational decisions, but also proactively exploit a reply strategy, such as investment in carbon emissions reduction. In this study, on the one hand, we characterizes the environment where the rapid development of information technologies allow retailers to have better information of the market demand than upstream manufacturers in the big data era; on the other hand, our findings can provide helpful suggestions for the governments better to set carbon tax to benefit the environment. Hence, we comprehensively examine how all kinds of factors, such as the market uncertainty, carbon tax and carbon emissions reduction affect the firms' decisions and the environment, which is not examined in the prior literature. We explore the retailer's information sharing decisions in the case where the manufacturer invests R&D in carbon emissions reduction, and the impact of carbon emissions reduction on the environment.

We explore whether the better-informed retailer has an incentive to share the demand information with the manufacturer in the uncertain market, and find that the manufacturer's reply strategy (i.e., carbon emissions reduction) has a pronounced effect on the retailer's decisions on information sharing. Even if information sharing makes the double marginalization problem more significant between the retailer and the manufacturer like traditional wisdoms (Yue and Liu, 2006; Ha et al., 2011), carbon emissions reduction can militate the double marginalization. As a result, the retailer may has an incentive to share the demand information with the manufacturer only if the manufacturer invests R&D in carbon emissions reduction. More specially, the retailer shares information with the manufacturer when the carbon tax is sufficiently high in the presence of carbon emissions reduction, whereas the retailer still has no incentives to share the demand information with the manufacturer in the absence of carbon emissions reduction. These findings not only contribute to the literature on information sharing (Yue and Liu, 2006; Li and Zhang, 2008; Mishra et al., 2009; Ha et al., 2011; Guo et al., 2014a; Shamir and Shin, 2015; Ha et al., 2017), but also explain why some retailers have incentives to share information with the manufacturers in the survey by Keifer (2010) and Forrester Research (Shang et al., 2016).

One expects that if the manufacturer receives no information, the better-informed retailer has a stronger bargaining power in the supply chain, i.e., the retailer gains more profit sharing from the supply chain. But this is not true. When the fluctuation in demand is relatively large, carbon emissions reduction allows the manufacturer to gain more profit sharing from the supply chain. This implies that in the uncertain market, the uninformed manufacturer can improve its bargaining with the better-informed retailer through proactive reply strategy, such as R&D in carbon emissions reduction.

Then we investigate the effect of carbon emissions reduction on the environment in the uncertain market, and surprisingly find that the manufacturer's carbon emissions reduction is not always beneficial to the environment if governments' carbon tax rate is under some conditions. The intuition is that in our study, the amount of carbon emission consists of the unit carbon emission and the demand. As traditional wisdoms (Yue and Liu, 2006; Ha et al., 2011) said, information sharing makes the double marginalization effect more significant, and further find that the greater the fluctuation in demand, the more serious the double marginalization; on the other hand, high carbon tax leads to much investments in carbon emissions reduction in order to decrease the cost of carbon tax, which alleviates the double marginalization effect. Hence, for high carbon tax, carbon emissions reduction benefit dominates the double marginalization. As a response, the retailer reduces its retail price, which increases the demand. In other words, high carbon tax may lead to a larger amount of carbon emission because of the manufacturer’s investments in carbon emissions reduction. As a result, the effect of carbon emissions reduction on the environment is decided by both the carbon tax and the demand fluctuation. More specially, the moderate carbon tax or the high carbon tax in the market with the high demand fluctuation may hurt the environment because of larger amount of carbon emissions in the uncertain market. These findings add insights to literature on carbon tax (Jin, 2014; Bouchery et al., 2012; Floros and Vlanchou, 2005; Lin and Li, 2011; Bruvoll and Larsen, 2004; Li et al., 2015) by revealing that the carbon tax can has an adverse effect on the environment; this study, on the other hand, tells us that only if the governments set carbon tax to reduce carbon emission, should they take into account the manufacturer’s reply strategy, such as R&D in carbon emissions reduction and the retailers’ ability about information prediction in the uncertain market. In particular, when manufacturers invest R&D in carbon emissions reduction, governments’ optimal decisions are to set a low carbon tax rate or decide a high carbon tax rate in the uncertain market with the low fluctuation.

6. Conclusions

With environmental legislations and carbon tax being introduced by ever more countries, a growing number of firms have begun investing in R&D to reduce carbon emissions. Yet, contrary to the conventional wisdom, this study reveals that a carbon tax is not always beneficial to the environment in a supply chain with a better-informed retailer. When the manufacturer does not invest in carbon emissions reduction, we find that information sharing always hurts the retailer but always benefits the manufacturer. It also hurts the supply chain because of the double marginalization effect. On the other hand, when the manufacturer invests in carbon emissions reduction, information sharing occurs when the carbon tax is sufficiently high and benefits the supply chain, consumer surplus, and social welfare. As a result, information sharing has the ability to coordinate preferences among the retailer, manufacturer, supply chain, consumer surplus, and social welfare. This coordinated region, however, diminishes or vanishes as the cost parameter of carbon emissions reduction increases. When the carbon tax is low, in contrast, the information sharing preferences of all the players differ substantially dependent on both the carbon tax and the cost parameter of the carbon emissions reduction. We further reveal not only that carbon emissions reduction benefits both the manufacturer and retailer, but that the retailer may engage in free-riding behavior and gain more profit sharing from the supply chain than in the case of no carbon emissions reduction. Nonetheless, carbon emissions reduction may hurt the environment by encouraging the production of more goods than in the no carbon emissions reduction scenario, especially when the carbon tax is moderate. Therefore, governments need to be careful when deciding upon a carbon tax rate.

Our study could be extended in several possible directions, including the adaptation of our monopolistic market structure model to examine competition between two or more retailers in the same supply chain. An interesting alternative would be to investigate competition in carbon emissions reduction between two or more manufacturers. A third possibility, given our finding of carbon emissions reduction's benefit to the retailer, would be to consider cooperative carbon emissions reduction between the manufacturer and retailer. In addition, it is also reasonable to consider the subsidy policy or other environment policies, including cap-and-trade system and carbon footprint for carbon emission reduction technology.

Declaration of competing interest

The authors declare no conflict of interest.

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We have no conflicts of interest to disclose.

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