Firms' green R&D cooperation behaviour in a supply chain: Technological spillover, power and coordination

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Abstract: In response to the global fight against climate change, a growing number of firms cooperate with their supply chain partners on green innovations. This study explores firms' green R&D cooperation behaviour in a two-echelon supply chain in which a manufacturer and a retailer first cooperate to invest green R&D and then organise production according to a wholesale price contract. Through a comparison with non-cooperation models, we evaluate the effects of green R&D cooperation on the economic, environmental and social performances of the supply chain while simultaneously considering the technological spillover and supply chain power relationship. Our findings show that the R&D cooperation's improvement of firms' economic performance is mainly determined by firms' own green contribution level. This level is dependent on firms' green R&D investment efficiency and spillover as well as on their relevant power relationship with their supply chain partners. Interestingly, there is a Pareto improvement region in which the green R&D cooperation has a positive impact on firms, customers and the environment. In the case of a non-Pareto improvement region, supply chain coordination can be achieved through a two-part tariff contract. This applies to all three of the supply chain power structures investigated in this research.

Keywords: green R&D; cooperation; technological spillover; low-carbon supply chain

1 Introduction

The Intergovernmental Panel on Climate Change's (IPCC's) recently published report has once again brought global warming to the world's attention. The report calls for urgent and unprecedented changes to reach the target of keeping the temperature increase below 1.5 °C, which is above pre-industrial levels, in order to reduce the risks to humans, ecosystems and sustainable development (IPCC 2018). Meanwhile, the continuous political debates on and media exposures of climate change issues have further raised the general public's environmental awareness. As a result, more customers are willing to pay premium prices for low-carbon products, and this shift in behaviour applies not only to environmentally conscious customers but also to the mainstream market (Bull, 2012; Kanchanapibul et al., 2014; Olsen et al., 2014). In this context, it is essential for companies to incorporate this increasing political and societal concern when developing effective green strategies to improve business competitiveness.

In response to the global fight against climate change, an increasing number of firms have been investing in green R&D and innovations with the aim to upgrade and modernise their operations and produce low-carbon products (Ishfaq et al., 2016; Liu and Chen, 2017). For example, in 2016, the Oil and Gas Climate Initiative (OGCI), a group that includes ten of the world's largest oil companies, created a fund to invest $1 billion in technologies to reduce carbon emissions from oil and natural gas (Pandey, 2016). The OGCI also stated that they would work closely with automotive manufacturers to increase vehicles' efficiency (Pandey, 2016). Moreover, Lenovo, one of the world's largest PC manufacturers, announced the breakthrough of an innovative low temperature solder manufacturing process, which reduces carbon emissions by 35% compared to the traditional PC manufacturing process (Lenovo Newsroom, 2017). In their climate change strategy, Lenovo also specified that the firm works with upstream/downstream partners to drive and facilitate carbon emissions reductions to support the transition to a low-carbon economy (Lenovo, 2016). In addition to individual efforts to make products and processes more carbon efficient, a growing industrial trend is to cooperate with upstream/downstream supply chain partners on green innovations and R&D to improve environmental performance (Vachon and Klassen, 2008; Caro et al., 2013).

Among the different modes of green R&D supply chain cooperation, one of the most common options reported in the literature is that an upstream firm and a downstream firm form a partnership to coordinate their green R&D decisions (Ishii, 2004; Ge et al., 2014; Yenipazarli, 2017). Through this mode, firms make green R&D decisions jointly to maximise the total profit of the partnership. Thereafter, the two firms make other operational decisions (e.g. prices and production quantity) sequentially to optimise their own profits in the second stage. However, while green R&D cooperation can have an immediate impact on unit carbon emissions reduction, it is likely to have a long-term effect of technological spillover, which refers to the diffusion of technology through technical exchanges or knowledge sharing between companies (Spenser, 2003; Ge et al., 2014). Technological spillover will have an impact on firms' R&D investment decisions and their ability to share other firms' innovations due to the spillover effect, which may damage firms' enthusiasm for R&D investment (Isaksson et al., 2016; Xu et al., 2017). Adding to the complexity of the problem, firms often have different internal technological/operational capabilities (e.g. efficiency of green R&D investment and the inter-firm power relationship between the supply chain members). For instance, the manufacturers (e.g. Toyota and Ford) are the dominant force in the automotive industry, and supermarket chains (e.g. Walmart and Tesco) are the leading forces in the grocery retail industry. In contrast, there is a more balanced power relationship between telecom service providers (e.g. AT&T and O2) and major cell phone makers (e.g. Apple and Samsung) in the telecommunications industry. The above observations motivated us to investigate the following key questions:

- Should firms cooperate with their supply chain partners on green R&D? If yes, what are the impacts of supply chain green R&D cooperation on firms, customers and the environment?
- How does firms' technological spillover affect supply chain firms' strategic (competition vs. cooperation) and operational (e.g. prices and green R&D investment) decisions and their consequential economic, environmental and social performances?
- What impact does the supply chain power structure have on firms' strategic and operational decisions and on their consequential economic, environmental and social performances?

Literature has increasingly focused on the importance of R&D cooperation for low carbon supply chain management. Previous research addressing this general question considered supply chain cooperation on green R&D and innovations (Dai et al., 2017; Ji et al., 2017; Yenipazarli, 2017), the spillover effect on R&D cooperation (Ge et al., 2014; Hu et al., 2017; Xu et al., 2017) and the effect of market and supply chain power structures on green cooperation (Shibata 2014; Chen et al. 2017b). Diverging from the above literature on low-carbon supply chain cooperation, we model firms' decision behaviour on green R&D cooperation in the form of centralised decision-making on green R&D investment, which is a highly common option related to green R&D supply chain cooperation. More importantly, we simultaneously consider technological spillover and supply chain power structures when examining how green R&D cooperation affects firms' financial performance, the customer surplus, the environment and social welfare.

Using a game theoretical modelling approach, we find that green R&D cooperation between supply chain partners always positively affects the supply chain's total profit, the environment, the customer surplus and social welfare. This finding applies to three supply chain power structures: Manufacturer Stackelberg, Vertical Nash, and Retailer Stackelberg. However, its impact on an individual firm's financial performance is more complicated because it is dependent on the firm's own green contribution level, which is determined by a firm's green R&D investment efficiency and its technological spillovers, as well as how it compares to its supply chain partners' contribution level. More importantly, we also find that in an asymmetric power structure, the supply chain leader should have a higher green contribution level than its follower in order to achieve sustainable green R&D cooperation that improves the cooperating firms' profitability and benefits both customers and the environment. Our research findings make important practical contributions. Our structured and systematic examination provides supply chain firms with clear strategic guidance on how to cooperate with supply chain partners in green R&D and considers their unique internal and external circumstances. Moreover, our findings offer support to firms when making optimal strategic and operational decisions regarding green R&D cooperation, thereby improving their business competitiveness. For policymakers, our results could help the development of appropriate policies to promote green R&D cooperation between supply chain firms, thereby supporting a sustainable low-carbon economy.

The rest of the paper is organised as follows: After reviewing the relevant literature in Section 2, Section 3 presents the cooperation and non-cooperation models and the equilibrium analysis. Then, in Section 4, we examine the impact of green R&D cooperation on firms' operational decisions and the economic, environmental and social performances of the supply chain, while also considering different power relationships. We subsequently consider spillover as an endogenous variable in Section 5, examining its effects on supply chain firms' decisions and performances. In Section 6, we analyse how the supply chain can be coordinated through a two-part tariff contract. Finally, we conclude our study by highlighting research insights, managerial and policy implications and future research directions.

2 Literature review

The paper is relevant to several research areas: (1) carbon emissions-sensitive demand; (2) cooperation for low-carbon supply chain management; (3) R&D spillover effect in low-carbon supply chains; and (4) the power perspective on low-carbon supply chains.

Due to increasing environmental awareness, an increasing number of customers are willing to pay a premium for low-carbon-attribute products (Olsen et al., 2014; Wang et al., 2017). Consequently, it is critical for firms to consider this shift in customer behaviour when making important strategic and operational decisions. This is also reflected in numerous previous studies on the incorporation of the carbon emissions-sensitive demand in determining pricing, ordering quantity and when making other supply chain decisions (Nouira et al., 2014; Zhang et al., 2015; Xu et al., 2017). Using the newsvendor model, Du et al. (2015) studied firms' behaviour and decision-making in the emission dependent supply chain. Their research found that the governmental environment policy and the market risk affect firms' bargaining power. Moreover, Luo et al. (2016) investigated the green technology investment problem of two competitive and heterogeneous manufacturers under competition and coopetition settings. They employed a demand function affected by the price and the environmental property of product. Using a similar demand setting, Chen et al. (2017a) examined how the market power structure and competition related to price and emissions affect firms' decisions and performances. The above two studies incorporated unit product carbon emissions as the environmental property in the demand function. In contrast, Xu et al. (2017) used the concept of carbon emissions intensity – i.e. the reduction in carbon emissions after the green technology investment – as the emissions attribute in their demand function. As customers are often more sensitive to the visible efforts of firms' low-carbon practices (Wang et al., 2017), we assume in this study that customer demand is sensitive to the reduction in unit carbon emissions (Xu et al., 2017) rather than unit product carbon emissions (Luo et al., 2006; Chen et al., 2017a).

Another relevant focus in literature stream considers supply chain environmental cooperation between manufacturers and their upstream suppliers or downstream retailers. For example, in their investigation of Canadian manufacturing plants, Klassen and Vachon (2003) discovered that supply chain collaboration has a significant impact on both the form and level of environmental technology investments. Other studies, e.g. Zhu et al. (2010) and Green et al. (2012), have also supported the view that supply chain members' environmental cooperation improves both environmental and economic performances and is critical for the success of a circular economy initiative. In addition, Jira and Toffel (2013) used data from the Carbon Disclosure Project's Supply Chain Program to investigate the conditions under which supply chain members are likely to coordinate efforts to address climate change.

More recently, Ji et al. (2017) investigated cooperation between a manufacturer and a retailer and considered online and offline shops. They also focused on how the cap-and-trade policy affects both economic performance and social welfare through modelling supply chain firms' emissions reduction behaviours. Moreover, and relevant to this research, Yenipazarli (2017) studied the impact of collaboration through supply chain contracts on suppliers' investment in the carbon emissions reduction of their product/production process and the consequential environmental impact on a supply chain. Further, Dai et al. (2017) applied a game-theoretical approach to examine two cooperative mechanisms between two supply chain members on green R&D investment: cartelisation and a cost-sharing contract. However, neither study considered technological spillover – an important element in green technology investment – and only one supply chain power structure setting was used. For instance, Yenipazarli (2017) assumed the downstream retailer as the Stackelberg leader; in contrast, Dai et al. (2017) assumed the upstream member as the Stackelberg leader. In fact, both spillover and supply chain power relationships have a significant impact on firms' decisions and performances, which will be further discussed below.

Technological spillovers refer to the diffusion of technology through a technical exchange or knowledge sharing between companies (Spenser, 2003; Ge et al., 2014). Despite growing interest among academics over the last two decades, the interface between technology cooperation and supply chain management remains an under-studied topic. Among the few studies conducted, Ge et al. (2014) considered spillover as an endogenous factor in their investigation of optimal choice between cooperative R&D investment and cartelisation. In another study involving a competitive setting of two manufacturers and one supplier, Wang et al. (2014) explored the potential impact of spillover on manufacturers' incentives to improve supplier reliability. Additionally, Xu and Wang (2017) studied the contracting pricing and emissions reduction of a two-echelon supply chain consisting of a retailer and a manufacturer and found that technological spillovers amplify the impact of free-ride behaviour. Moreover, Hu et al. (2017) used the concept of technological spillover to examine the supply-side implications of open technologies. They determined that firms must understand the supply chain context and open technologies' far-reaching impact prior to reaching decisions on technology strategies. Even fewer studies have considered the effect of vertical technological spillovers on firms' decisions and performances in the context of a low-carbon supply chain. Among them, Xu et al. (2017) considered technological spillover in their investigation of supply chain decisions and coordination. However, in their research, technological spillover was viewed as reducing the production cost but not carbon emissions, which is not reasonable for green technology investment.

Numerous prior studies related to supply chain management have considered power relationships in various research problems (Shi et al., 2013; Benton and Maloni, 2005; Chen and Wang, 2015). For instance, Shibata (2014) examined R&D investment spillovers across different market structures and found that non-cooperative R&D is likely preferred as competition intensifies. However, the study was not conducted in the context of green/low-carbon supply chain management. Additionally, based on their investigation of power influences on organisational responses to the implementation of sustainability practices, Touboulic et al. (2014) claimed that the power dynamics between supply chain partners affect the sharing of sustainability-related value and risks. Further, and also from a power perspective, Chen et al. (2017b) applied a game-theoretic approach to analyse the impact of supply chain power relationships on firms' decisions as well as the economic and environmental performances of a two-echelon supply chain. Based on their research, they found that supply chain power relationships have a significant impact on economic and environmental performance. Different from the previous literature, our research models R&D cooperation behaviour for the low-carbon supply chain and considers carbon emissions sensitive demand, technological spillover and the supply chain power structure.

In summary, despite increasing interest among practitioners and academics and an increasing number of studies on environment cooperation covering various aspects including power relationships, technological spillover and coordination, to be best of our knowledge, there is limited research that simultaneously takes into account all those important aspects when exploring the role of R&D cooperation in the low carbon supply chain management. Our research aims to fill this gap in the literature and systematically analyse the influence of these factors in relation to the impact of green R&D cooperation regarding supply chain firms' financial performance, consumer surplus, the environment and social welfare.

3. The models and equilibrium analysis

3.1. The model

We consider a two-echelon supply chain composed of a manufacturer and a retailer. The retailer purchases products from the manufacturer and then sells them to end customers. The demand faced by the retailer is price- and carbon emissions-sensitive, and the decision variables of the retailer are the retail price and green R&D investment, which are directly associated with unit carbon emissions reduction. The decision variables of the manufacturer are the wholesale price and its green R&D investment. There are two stages game involved in the supply chain as illustrated in Figure 1. In the first stage game, the manufacturer and retailer make strategic decision on green R&D investment and they decide whether to cooperate with their supply chain partner in the form of centralized decision on green R&D investment. In the second stage game, the manufacturer and retailer make operational decision on wholesale and retail prices and the sequence of decisions depends on supply chain power structures including Manufacturer Stackelberg (MS), Vertical Nash (VN), and Retailer Stackelberg (RS). Throughout this paper, we use the notations presented in Table 1.

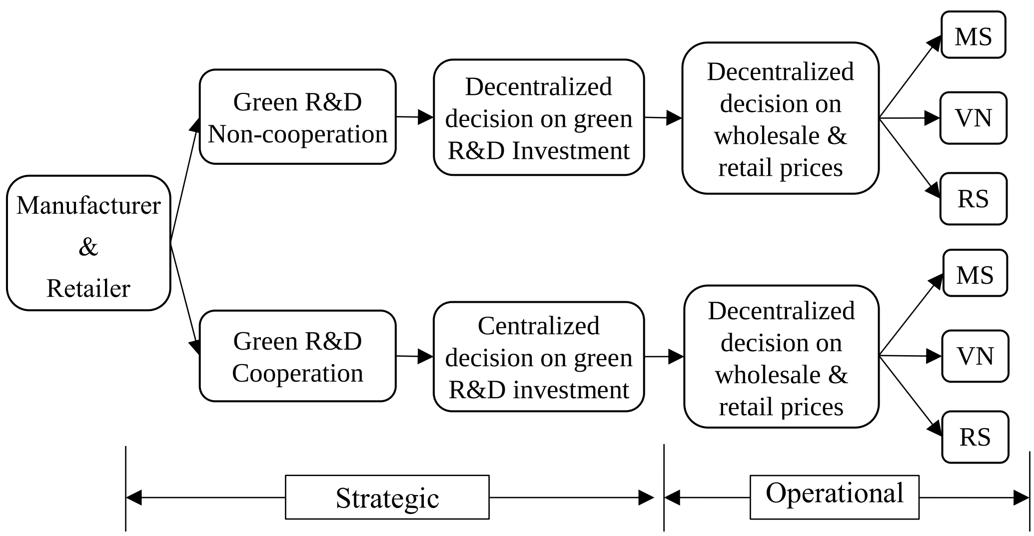


Figure 1: Decision framework

In consideration of the literature (Tsay and Agrawal, 2000; Luo et al., 2016; Xu et al., 2017), the demand faced by the retailer is $q = \alpha - \beta p + \gamma(e_m + e_r + \theta_m e_m + \theta_r e_r)$. α is the maximum market demand (end-customer demand). β and γ are the price sensitivity and carbon emissions reduction sensitivity, respectively (Xu et al., 2017): $\beta > 0$ and $\gamma > 0$. Without green R&D investment, $q = \alpha - \beta p > 0$; then $q_0 = \alpha - \beta c > 0$. For the non-cooperation model, the manufacturer's profit $\pi_m(w, e_m)$ is:

$$\pi_m(w, e_m) = (w - c)[\alpha - \beta p + \gamma(e_m + e_r + \theta_m e_m + \theta_r e_r)] - \frac{1}{2} t_m e_m^2 \quad (1)$$

The first part of the formula represents the wholesale profit on the product, and the second part indicates the manufacturer's green R&D investment.

Table 1: Notations

Notation	Descriptions
c	Unit production cost, which includes the material cost and the process cost.
w	Unit wholesale price, $w > c$.
p	Unit retail price, $p > w$.
q	Demand faced by the retailer.
e_m, e_r	Unit carbon emissions reduction after the green R&D investment of the manufacturer and retailer, respectively.
E	Total carbon emissions reduction after the green R&D investment of the manufacturer and retailer, $E = (e_m + e_r)q$.
t_m, t_r	Green R&D investment cost coefficient of the manufacturer and retailer, respectively.
T_m, T_r	Green R&D investment of the manufacturer and retailer, respectively, $T_m = \frac{1}{2} t_m e_m^2$, $T_r = \frac{1}{2} t_r {e_r}^2$.
θ_m, θ_r	The spillover rate of the manufacturer and retailer to its partner, respectively, $0 \le \theta_m \le 1$, $0 \le \theta_r \le 1$.
$\pi_m\,(w, e_m)$	Manufacturer's profit.
$\pi_r(p, e_r)$	Retailer's profit.
CS	Customer surplus, $CS = \int_p^{\frac{\alpha+\gamma(e_m+e_r+\theta_m e_m+\theta_r e_r)}{\beta}} q(x)dx$.
c_e	The cost of controlling environmental pollution caused by unit carbon emissions.
SW	Social welfare, $SW = CS + \pi_m\,(w, e_m) + \pi_r(p, e_r) + c_e E$.
M	The retailer's lump-sum payment to the manufacturer.

Similarly, for the non-cooperation model, the retailer's profit $\pi_r(p, e_r)$ is:

$$\pi_r(p, e_r) = (p - w)[\alpha - \beta p + \gamma(e_m + e_r + \theta_m e_m + \theta_r e_r)] - \frac{1}{2} t_r e_r^2 \tag{2}$$

The supply chain's profit in the cooperation model is:

$$\pi_t^c(e_m, p, e_r) = \pi_m(w, e_m) + \pi_r(p, e_r) \tag{3}$$

The supply chain's profit in the non-cooperation model is:

$$\pi_t^n(w, e_m, p, e_r) = \pi_m(w, e_m) + \pi_r(p, e_r) \tag{4}$$

3.2 Non-cooperation models

We first investigate non-cooperation models as a benchmark. Below, we describe the decision sequences for three power structures (MS, VN and RS) in the non-cooperation models. Each model includes two stages.

MS non-cooperation model: In the first stage, the manufacturer and retailer independently and simultaneously decide on their individual green R&D investments to maximise their own profits. In the second stage, the manufacturer offers a wholesale price w; then the retailer decides on its retail price p in response. Thus, the process of the MS non-cooperation model can be described as follows:

$$\left.\begin{matrix} \max\limits_{e_m} \pi_m(w, e_m) \\ \max\limits_{e_r} \pi_r(p, e_r) \end{matrix}\right\} \to \max_{w} \pi_m(w, e_m) \to \max_{p} \pi_r(p, e_r)$$

VN non-cooperation model: In the first stage, the manufacturer and retailer independently and simultaneously decide on their individual green R&D investments to maximise their own profits. In the second stage, the manufacturer and retailer independently and simultaneously decide on their wholesale price and retail price, respectively. Thus, the process of the VN non-cooperation model can be described as follows:

$$\left.\begin{matrix} \max\limits_{e_m} \pi_m(w, e_m) \\ \max\limits_{e_r} \pi_r(p, e_r) \end{matrix}\right\} \to \left\{\begin{matrix} \max\limits_{w} \pi_m(w, e_m) \\ \max\limits_{p} \pi_r(p, e_r) \end{matrix}\right.$$

RS non-cooperation model: In the first stage, the manufacturer and retailer independently and simultaneously decide on their individual green R&D investments to maximise their own profits. In the second stage, the retailer offers a retail price p; then the manufacturer decides on its wholesale price w in response. Thus, the process of the RS non-cooperation model can be described as follows:

$$\left.\begin{matrix} \max\limits_{e_m} \pi_m(w, e_m) \\ \max\limits_{e_r} \pi_r(p, e_r) \end{matrix}\right\} \to \max_{p} \pi_r(p, e_r) \to \max_{w} \pi_m(w, e_m)$$

All three models are multi-stage non-cooperative games, and we can use backward induction to solve them. Table 2 lists the manufacturer's optimal wholesale price (w^{nj}) and unit carbon emissions reduction after green R&D investment (e_m^{nj}), as well as the retailer's optimal retail price (p^{nj}) and unit carbon emissions reduction after green R&D investment (e_r^{nj}) for non-cooperation, where $j = m, v, n$ represents the MS, VN and RS models, respectively.

3.3 Cooperation models

In this section, we explore the cooperation models and describe the decision sequences for three power structures (MS, VN and RS) in these models. Environmental cooperation in this study is modelled through centralised decision making for a green R&D investment decision. In contrast to the integrated supply chain in which all the decisions (e.g. prices and/or production quantity decisions) are centralised, the manufacturer and the retailer individually make the wholesale and retail price decision following the joint green R&D investment decision. Each model includes two stages.

MS cooperation model: In the first stage, the manufacturer and retailer jointly decide on green R&D investments to maximise the supply chain's total profit. In the second stage, the manufacturer offers a wholesale price w; then the retailer decides on its retail price p in response. Thus, the process of the MS cooperation model can be described as follows:

$$\max_{e_m, e_r} \pi_t(e_m, p, e_r) \rightarrow \max_{w} \pi_m(w, e_m) \rightarrow \max_{p} \pi_r(p, e_r)$$

VN cooperation model: In the first stage, the manufacturer and retailer jointly decide on green R&D investments to maximise the supply chain's total profit. In the second stage, the manufacturer and retailer simultaneously decide on their wholesale and retail prices. Thus, the process of the VN cooperation model can be described as follows:

$$\max_{e_m, e_r} \pi_t(e_m, p, e_r) \rightarrow \begin{cases} \max\limits_{w} \pi_m(w, e_m) \\ \max\limits_{p} \pi_r(p, e_r) \end{cases}$$

RS cooperation model: In the first stage, the manufacturer and retailer jointly decide on green R&D investments to maximise the supply chain's total profit. In the second stage, the retailer offers a retail price p; then the manufacturer decides on its wholesale price w in response. Thus, the process of the RS cooperation model can be described as follows:

$$\max_{e_m, e_r} \pi_t(e_m, p, e_r) \rightarrow \max_{p} \pi_r(p, e_r) \rightarrow \max_{w} \pi_m(w, e_m)$$

All three models are multi-stage games, and we can use backward induction to solve them. Table 2 lists the manufacturer's optimal wholesale price (w^{cj}) and unit carbon emissions reduction after green R&D investment(e_m^{cj}). It also lists the retailer's optimal retail price (p^{cj}) and unit carbon emissions reduction after green R&D investment (e_r^{cj}) for cooperation, where $j = m, v, n$ represents the MS, VN and RS models, respectively.

Table 2: Optimal decisions associated with the non-cooperation and cooperation models

Models		MS model ($j = m$)	VN model ($j = v$)	RS model ($j = r$)
Non-cooperation	w^{nj}	$c + \frac{q_0}{\beta(2 - 2G_m - G_r)}$	$c + \frac{3q_0}{\beta(9 - 8G_m - 8G_r)}$	$c + \frac{q_0}{2\beta(2 - G_m - 2G_r)}$
	p^{nj}	$w^{nm} + \frac{q_0}{2\beta(2 - 2G_m - G_r)}$	$w^{nv} + \frac{3q_0}{\beta(9 - 8G_m - 8G_r)}$	$w^{nr} + \frac{q_0}{\beta(2 - G_m - 2G_r)}$
	e_m^{nj}	$\frac{q_0\gamma(1 + \theta_m)}{2t_m\beta(2 - 2G_m - G_r)}$	$\frac{2q_0\gamma(1 + \theta_m)}{t_m\beta(9 - 8G_m - 8G_r)}$	$\frac{q_0\gamma(1 + \theta_m)}{4t_m\beta(2 - G_m - 2G_r)}$
	e_r^{nj}	$\frac{q_0\gamma(1 + \theta_r)}{4t_r\beta(2 - 2G_m - G_r)}$	$\frac{2q_0\gamma(1 + \theta_r)}{t_r\beta(9 - 8G_m - 8G_r)}$	$\frac{q_0\gamma(1 + \theta_r)}{2t_r\beta(2 - G_m - 2G_r)}$
Cooperation	w^{cj}	$c + \frac{q_0}{\beta(2 - 3G_m - 3G_r)}$	$c + \frac{3q_0}{\beta(9 - 16G_m - 16G_r)}$	$c + \frac{q_0}{2\beta(2 - 3G_m - 3G_r)}$
	p^{cj}	$w^{cm} + \frac{q_0}{2\beta(2 - 3G_m - 3G_r)}$	$w^{cv} + \frac{3q_0}{\beta(9 - 16G_m - 16G_r)}$	$w^{cr} + \frac{q_0}{\beta(2 - 3G_m - 3G_r)}$
	e_m^{cj}	$\frac{3q_0\gamma(1 + \theta_m)}{4t_m\beta(2 - 3G_m - 3G_r)}$	$\frac{4q_0\gamma(1 + \theta_m)}{t_m\beta(9 - 16G_m - 16G_r)}$	$\frac{3q_0\gamma(1 + \theta_m)}{4t_m\beta(2 - 3G_m - 3G_r)}$
	e_r^{cj}	$\frac{3q_0\gamma(1 + \theta_r)}{4t_r\beta(2 - 3G_m - 3G_r)}$	$\frac{4q_0\gamma(1 + \theta_r)}{t_r\beta(9 - 16G_m - 16G_r)}$	$\frac{3q_0\gamma(1 + \theta_r)}{4t_r\beta(2 - 3G_m - 3G_r)}$

In Table 2, $G_m = \frac{\gamma^2(1+\theta_m)^2}{4t_m\beta}$ and $G_r = \frac{\gamma^2(1+\theta_r)^2}{4t_r\beta}$. G_i decreases in its own green R&D investment cost coefficient (t_i), but it increases in its spillover rate to its partner (θ_i). In this sense, G_i indicates the *green contribution level* of the manufacturer ($i = m$) and retailer ($i = r$) and their cooperation in the supply chain. Thus, G_m represents the manufacturer's *green contribution level*, and G_r represents the retailer's *green contribution level*. The green R&D investment cost coefficient (t_i) decreases in the green R&D investment efficiency. A low value of the coefficient indicates a higher level of investment efficiency, meaning that it requires less investment to achieve the same amount of reduction in unit carbon emissions. A high value of the coefficient indicates a lower level of investment efficiency, meaning that it requires more investment to achieve the same amount of reduction in unit carbon emissions.

To guarantee the existence of prices and carbon emissions reduction decisions in the MS and RS models, we assume that:

$$G_m + G_r < \frac{2}{3} \text{ (GC)}$$

Similarly, to guarantee the existence of prices and carbon emissions reduction decisions in the VN model, we assume that:

$$G_m + G_r < \frac{9}{16} \text{ (GCV)}$$

These types of assumptions appeared frequently in the literature (Ge et al., 2014; Gupta, 2008). The above conditions, (GC) and (GCV), mean that the *green contribution level* of the manufacturer and the retailer should not be too large. In other words, the green R&D investment cost coefficient of both the manufacturer and the retailer (t_m and t_r) cannot be too small. A small value of t_m and t_r will reduce firms' incentives to invest in green R&D.

4 Effects of cooperation

In this section, we examine the effects of green R&D investment cooperation on firms' decisions regarding prices and green R&D investment level; the consequential economic performance of each firm individually and the supply chain as a whole; and the impacts on the environment and customers.

4.1 The effects of cooperation on firms' decisions

Regarding the effect of cooperation on the firms' decisions, we have the following lemma:

Lemma 1: $T_r^{cj} > T_r^{nj},\ T_m^{cj} > T_m^{nj},\ e_m^{cj} > e_m^{nj},\ e_r^{cj} > e_r^{nj},\ w^{cj} > w^{nj},\ p^{cj} > p^{nj},\ q^{cj} > q^{nj},$ *where* $j = m, v, r$.

This lemma means that in each supply chain power structure, compared to the non-cooperation model, both the manufacturer and the retailer will invest more in green R&D in the cooperation model and achieve a greater reduction in their unit carbon emissions after green R&D investment. This is in line with the existing literature claiming that supply chain cooperation increases the level of green technology investment and improves environmental performance (Klassen and Vachon, 2003; Vachon and Klassen, 2008). It also leads to higher wholesale and retail prices. Although the retail price is higher in the cooperation model than in the non-cooperation model, demand in the cooperation model is higher than that in the non-cooperation model due to customers' sensitivity to firms' carbon emissions reduction efforts (Olsen et al., 2014; Wang et al., 2017).

4.2 The effect of cooperation on profits

Knowing whether cooperation can improve firms' profits can help managers to make better cooperation decisions. Therefore, we first derive the following proposition regarding cooperation's effect on the supply chain's total profit.

Proposition 1： $\pi_t^c\left(e_m^{cj}, p^{cj}, e_r^{cj}\right) > \pi_t^n\left(w^{nj}, e_m^{nj}, p^{nj}, e_r^{nj}\right)$, *where* $j = m, v, r$.

Proposition 1 implies that, in each power structure, the supply chain's profit is always higher in the cooperation model than in the non-cooperation model. It supports Zhu et al. (2010) and Green et al.'s (2012) view that environmental cooperation within the supply chain improves not only its environmental performance but also its economic performance. This can be explained by the fact that, in the green R&D investment stage, the cooperation model's objective is to maximise the supply chain's total profit, while the non-cooperation model's objective is to maximise each individual firm's profit. Since the green R&D cooperation is in the form of centralized decision on the two firms' green R&D investment, the cooperation cost is insignificant and assumed to not incur additional cost. Therefore, the green R&D investment cooperation always increases the total profit of the supply chain.

Now, we look at the impact of green R&D cooperation on individual firms' financial performance. To determine the effect of cooperation on the manufacturer's financial performance, we have the following proposition:

Proposition 2: *(1) In the MS model, if* $0 < G_m < f_r^m(G_r)$ *, then* $\pi_m(w^{cm}, e_m^{cm}) > \pi_m(w^{nm}, e_m^{nm})$*; if* $f_r^m(G_r) < G_m < \frac{2}{3}$*, then* $\pi_m(w^{cm}, e_m^{cm}) < \pi_m(w^{nm}, e_m^{nm})$*, where* $f_r^m(G_r) = \frac{4+68G_r-27G_r^2-(2+3G_r)\sqrt{4-4G_r+81G_r^2}}{2(4+36G_r)}$.

(2) In the VN model, if $0 < G_m < f_r^v(G_r)$*, then* $\pi_m(w^{cv}, e_m^{cv}) > \pi_m(w^{nv}, e_m^{nv})$*; if* $f_r^v(G_r) < G_m < \frac{9}{16}$*, then* $\pi_m(w^{cv}, e_m^{cv}) < \pi_m(w^{nv}, e_m^{nv})$*, where* $f_r^v(G_r) = \frac{9+16G_r-\sqrt{81-288G_r+1024G_r^2}}{16}$.

(3) In the RS model, if $0 < G_r < \frac{4}{9}$ *and* $0 < G_m < f_r^r(G_r)$*, or if* $\frac{4}{9} < G_r < \frac{2}{3}$ *and* $f_r^r(G_r) < G_m < \frac{2}{9}$*, then* $\pi_m(w^{cr}, e_m^{cr}) > \pi_m(w^{nr}, e_m^{nr})$*; if* $0 < G_r < \frac{4}{9}$ *and* $f_r^r(G_r) < G_m < \frac{2}{3}$*, or if* $\frac{4}{9} < G_r <$

$\frac{2}{3}$ *and* $0 < G_m < f_r^r(G_r)$, *then* $\pi_m(w^{cr}, e_m^{cr}) < \pi_m(w^{nr}, e_m^{nr})$, *where* $f_r^r(G_r) = \frac{16-32G_r+27G_r^2-(4-3G_r)\sqrt{16-56G_r+81G_r^2}}{2(8-18G_r)}$.

For the manufacturer, parts (1) and (2) of Proposition 2 mean that when there is no cooperation cost, whether its profit increases or decreases in the MS and VN power structures depends on its own green contribution level. More specifically, if its green contribution level is lower than a critical threshold ($f_r^m(G_r)$ in MS or $f_r^v(G_r)$ in VN), which is related to the retailer's green contribution level, then the manufacturer will gain more profit in the cooperation model than in the non-cooperation model. On the contrary, if the manufacturer's green contribution is higher than the threshold, then it will gain less profit in the cooperation model than in the non-cooperation model.

In the RS power structure, part (3) of Proposition 2 means that when there is no cooperation cost, whether the manufacturer's profit increases or decreases depends on the green contribution level of both the retailer and the manufacturer. More specifically, if the retailer's green contribution level is low (high) and the manufacturer's green contribution level is also lower (higher) than a critical threshold, $f_r^r(G_r)$, which is related to the retailer's green contribution level, then the manufacturer will gain more profit in the cooperation model than in the non-cooperation model. In this case, the green contribution level of the manufacturer, a follower, matches the green contribution level of the retailer, a leader. On the contrary, if the retailer's green contribution level is low (high) but the manufacturer's green contribution level is higher (lower) than $f_r^r(G_r)$, then the manufacturer will gain less profit in the cooperation model than in the non-cooperation model. In this case, there is a mismatch between the green contribution levels of the manufacturer (Stackelberg follower) and the retailer (Stackelberg leader).

To determine the effect of cooperation on the retailer's financial performance, we have the following proposition:

Proposition 3: *(1) In the MS model, if* $0 < G_m < \frac{4}{9}$ *and* $0 < G_r < f_m^m(G_m)$*, or if* $\frac{4}{9} < G_m < \frac{2}{3}$ *and* $f_m^m(G_m) < G_r < \frac{2}{9}$*, then* $\pi_r(p^{cm}, e_r^{cm}) > \pi_r(p^{nm}, e_r^{nm})$*; if* $0 < G_m < \frac{4}{9}$ *and* $f_m^m(G_m) < G_r <$

$\frac{2}{3}$, *or if* $\frac{4}{9} < G_m < \frac{2}{3}$ *and* $0 < G_r < f_m^m(G_m)$, *then* $\pi_r(p^{cm}, e_r^{cm}) < \pi_r(p^{nm}, e_r^{nm})$, *where* $f_m^m(G_m) = \frac{16-32G_m+27G_m^2-(4-3G_m)\sqrt{16-56G_m+81G_m^2}}{2(8-18G_m)}$.

(2) In the VN model, if $0 < G_r < f_m^v(G_m)$, *then* $\pi_r(p^{cv}, e_r^{cv}) > \pi_r(p^{nv}, e_r^{nv})$; *if* $f_m^v(G_m) < G_r < \frac{9}{16}$, *then* $\pi_r(p^{cv}, e_r^{cv}) < \pi_r(p^{cv}, e_r^{nv})$; *where* $f_m^v(G_m) = \frac{9+16G_m-\sqrt{81-288G_m+1024G_m^2}}{16}$.

(3) In the RS model, if $0 < G_r < f_m^r(G_m)$, *then* $\pi_r(p^{cr}, e_r^{cr}) > \pi_r(p^{nr}, e_r^{nr})$; *if* $f_m^r(G_m) < G_r < \frac{2}{3}$, *then* $\pi_r(p^{cr}, e_r^{cr}) < \pi_r(p^{nr}, e_r^{nr})$, *where* $f_m^r(G_m) = \frac{4+68G_m-27G_m^2-(2+3G_m)\sqrt{4-4G_m+81G_m^2}}{2(4+36G_m)}$.

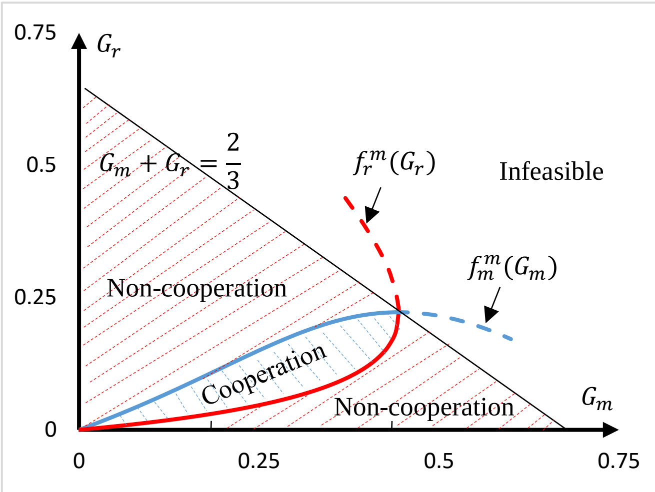
For the retailer, part (1) of Proposition 3 means that when there is no cooperation cost, whether its profit increases or decreases in the MS power structure depends on the green contribution level of both the manufacturer and the retailer. More specifically, if the manufacturer's green contribution level is low (high) and the retailer's green contribution level is also lower (higher) than a critical threshold, $f_m^m(G_m)$, which is related to the manufacturer's green contribution level, then the retailer will gain more profit in the cooperation model than in the non-cooperation model. On the contrary, if the manufacturer's green contribution level is low (high) but the retailer's green contribution level is higher (lower) than $f_m^m(G_m)$, then the retailer will gain less profit in the cooperation model than in the non-cooperation model. Parts (2) and (3) of Proposition 3 mean that, in the VN and RS power structures, whether the retailer's profit increases or decreases depends on its own green contribution level. More specifically, this level is lower than the critical thresholds ($f_m^v(G_m)$ in VN and $f_m^r(G_m)$ in RS), which are related to the manufacturer's green contribution level. Therefore, the retailer will gain more profit in the cooperation model than in the non-cooperation model. On the contrary, if the retailer's green contribution is higher than the threshold, then the retailer will gain less profit in the cooperation model than in the non-cooperation model.

From the analysis of Propositions 2 and 3, we learn that when the Stackelberg leader's green contribution level is low, the leader can gain economic benefits through cooperation, as a joint decision on green R&D investment will increase the supply chain's total profit (Proposition 1). With superior power over its supply chain partner and a low green contribution level, which are reflected in low R&D investment and/or low technological spillover, it is more likely for the leader to receive a larger share of this increased total profit. In contrast, when the Stackelberg leader's green contribution level is high, the leader cannot benefit economically through cooperation since it contributes more to the increased total profits. Therefore, in this case, it is better for the leader not to engage in green cooperation.

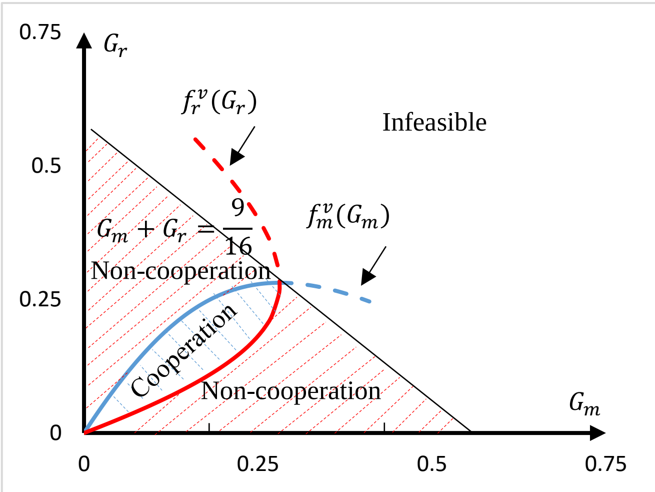
Similarly, in the symmetric power structure, the decision regarding cooperation is mainly dependent on each supply chain member's own green contribution level. Although cooperation will increase total profits, distribution of the increased profits is more balanced in the symmetric power structure. Therefore, it is more beneficial to engage in green cooperation when each supply chain member's own green contribution level is low. Intuitively, firms can gain more benefit to cooperate with the supply chain partners that are more advanced or capable of green R&D. For Stackelberg followers, economic benefits can only be gained when the manufacturer's and retailer's green contribution levels match. When followers have a higher green contribution level as compared to Stackelberg leaders, they will lose out by contributing more to the increased profit but receiving a smaller share of it due to their relevant weaker power in the contract negotiation of wholesale price. Alternatively, cooperation does not take place if the leader has a higher green contribution level. Compared to existing studies (Dai et al., 2017; Xu et al., 2017), the above analysis captures a much wider range of outcomes for green R&D cooperation's impacts on firms' financial performance. Prior works, e.g. Dai et al. (2017) and Xu et al. (2017), have only considered the supply chain setting of the upstream supplier as the Stackelberg leader and the downstream manufacturer as the Stackelberg follower.

The above analysis indicates that cooperation could have a positive or negative impact on individual firms' economic performance. Supply chain firms face the dilemma of profit maximisation for individual firms and/or the supply chain as a whole (Chen et al., 2017b). To ensure the success of supply chain cooperation, it is critical to achieve a win-win outcome for both parties. Therefore, from Propositions 2 and 3, we derive the following corollary, as shown in Figure 2:

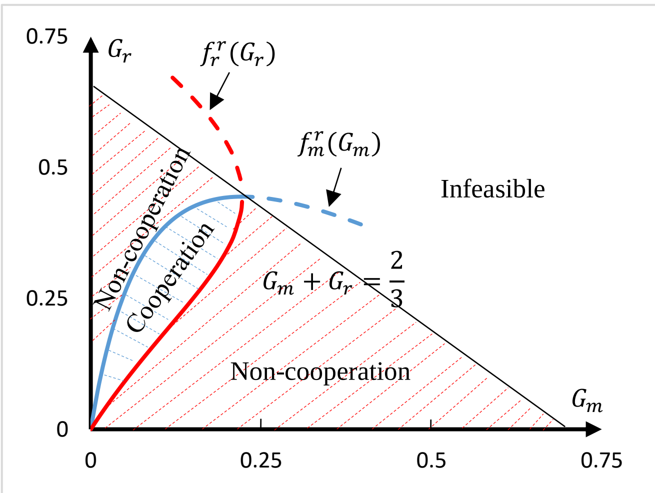
Corollary 1: *If* $0 < G_m < f_r^j(G_r)$ *and* $0 < G_r < f_m^j(G_m)$, *then* $\pi_m\left(w^{cj}, e_m^{cj}\right) > \pi_m\left(w^{nj}, e_m^{nj}\right)$ *and* $\pi_r\left(p^{cj}, e_r^{cj}\right) > \pi_r\left(p^{nj}, e_r^{nj}\right)$, *where* $j = m, v, r$.



(a) Pareto area in the MS model



(b) Pareto area in the VN model



(c) Pareto area in the RS model

Figure 2: Pareto area in different supply chain power structures

As Figure 2 shows, in each power structure, if the green contribution levels of the manufacturer and the retailer are lower than the corresponding thresholds, which are related to their partner's green contribution levels, then both firms will gain more profits in the cooperation model than in the non-cooperation model. In this scenario, the manufacturer and retailer prefer cooperation, thus leading to a win-win situation. Furthermore, the area for this Pareto improvement region varies between different supply chain power structures. For instance, in the MS model, this decision region is positioned in the area where $f_m^m(G_m) < f_r^m(G_r)$. In the RS model, this decision region is positioned in the area where $f_r^r(G_r) < f_m^r(G_m)$, which means that the Pareto area of green R&D investment cooperation will only exist if the Stackelberg leader contributes more than the Stackelberg follower. In the VN model, this decision region is placed in the area where $f_r^n(G_r) = f_m^n(G_m)$. The results support Touboulic et al.'s (2014) view that the power relationship markedly influences the sharing of sustainability-related value between supply chain members. Therefore, to sustain the green R&D cooperation in the supply chain and maximize the impact on carbon emission reduction, it is essential for supply chain leaders to make more contribution towards green R&D. Figure 2 also shows that in each supply chain power structure, besides the area for Pareto improvement, there exist two feasible regions in which one firm benefits from cooperation while the other is worse off. In such a case, the latter firm will certainly not embrace green cooperation with the supply chain partner. Therefore, it is important to fairly distribute the financial benefit gained from the green R&D cooperation.

4.3 The effect of cooperation on customers and the environment

Regarding the effect of cooperation on customers and the environment, we have the following proposition:

Proposition 4: $E^{cj} > E^{nj},\ CS^{cj} > CS^{nj}$ *and* $SW^{cj} > SW^{nj}$, *where* $j = m, v, r$.

As Proposition 4 represents, in each power structure, the total carbon emissions reduction after green R&D investment is greater in the cooperation model than in the non-cooperation model, which benefits the environment. At the same time, although the retail price is higher in the cooperation model than in the non-cooperation model, the customer surplus is also higher in the former than in the latter. This is because the extent of environmental performance improvement is more substantial than the increase of the retail price. Thus, cooperation also benefits customers. Therefore, where *Pareto improvement* can be achieved through cooperation, as highlighted in Figure 2, it is a sustainable strategy that not only improves the supply chain's economic performance but also contributes to the environment and social welfare, thus delivering a win-win-win situation.

5 Effects of spillover

Section 4's analysis indicates that firms' green contribution level, which is influenced by their green R&D investment cost coefficients and spillovers, significantly impacts their strategic decisions on green R&D cooperation. In addition, firms can voluntarily increase spillover by improving communication or knowledge transfer (Ge et al., 2014). Therefore, in this section, we regard *spillover* as an endogenous factor and examine its effects on supply chain firms' decisions and performances.

5.1 The effects of spillover on decisions

Regarding the effects of spillover on decisions, we have the following proposition:

Lemma 2: *(1) For the non-cooperation model,* T_r^{nj}*,* T_m^{nj}*,* e_m^{nj}*,* e_r^{nj}*,* w^{nj}*,* p^{nj}*, and* q^{nj} *all increase in* θ_m *and* θ_r*, where* $j = m, v, r$.

(2) For the cooperation model, T_r^{cj}*,* T_m^{cj}*,* e_m^{cj}*,* e_r^{cj}*,* w^{cj}*,* p^{cj}*, and* q^{cj} *all increase in* θ_m *and* θ_r*, where* $j = m, v, r$.

Part (1) of Lemma 2 means that in each power structure, for the non-cooperation model, if the manufacturer's or retailer's spillover is enhanced, then both the manufacturer and the retailer will invest more in green R&D and achieve greater reductions in their unit carbon emissions. This also leads to higher wholesale and retail prices. Moreover, due to customers' environmental awareness, demand increases. Part (2) of Lemma 2 implies that in each power structure, the findings for the non-cooperation model also apply to the cooperation model. This result demonstrates that, in order to maximize the positive impact on carbon emission reduction, firms should always seek ways (e.g., improved communication or knowledge transfer) to enhance technological spillover regardless of green R&D cooperation or not.

5.2 The effects of spillover on profits

Regarding the effects of spillover on the profits of the retailer, manufacturer and the whole supply chain, we have the following proposition:

Proposition 5: (1) *For the non-cooperation model,* $\pi_r(p^{nj}, e_r^{nj})$*,* $\pi_m(w^{nj}, e_m^{nj})$*, and* $\pi_t^n(w^{nj}, e_m^{nj}, p^{nj}, e_r^{nj})$ *increase in* θ_m *and* θ_r*, where* $j = m, v, r$.

(2) For the cooperation model, $\pi_t^c(e_m^{cj}, p^{cj}, e_r^{cj})$ *increases in* θ_m *and* θ_r*,* $\pi_m(w^{cj}, e_m^{cj})$ *increases in* θ_r*, and* $\pi_r(p^{cj}, e_r^{cj})$ *increases in* θ_m*, where* $j = m, v, r$.

(3) a) For the MS cooperation model, if $G_m - G_r > \frac{2}{9}$ $(< \frac{2}{9})$*, then* $\pi_m(w^{cm}, e_m^{cm})$ *decreases (increases) in* θ_m *and* $\pi_r(p^{cm}, e_r^{cm})$ *increases (decreases) in* θ_r*; only if* $G_m - G_r = \frac{2}{9}$ *will both* $\pi_m(w^{cm}, e_m^{cm})$ *and* $\pi_r(p^{cm}, e_r^{cm})$ *achieve their maximum profits.*

b) For the VN cooperation model, if $G_m > G_r$ $(G_m < G_r)$*, then* $\pi_m(w^c, e_m^c)$ *decreases (increases) in* θ_m *and* $\pi_r(p^c, e_r^c)$ *increases (decreases) in* θ_r*; only if* $G_m = G_r$ *will both* $\pi_m(w^c, e_m^c)$ *and* $\pi_r(p^c, e_r^c)$ *achieve their maximum profits.*

c) For the RS cooperation model, if $G_r - G_m > \frac{2}{9}$ $(< \frac{2}{9})$*, then* $\pi_m(w^{cr}, e_m^{cr})$ *increases (decreases) in* θ_m *and* $\pi_r(p^{cr}, e_r^{cr})$ *decreases (increases) in* θ_r*; only if* $G_r - G_m = \frac{2}{9}$ *will both* $\pi_m(w^{cr}, e_m^{cr})$ *and* $\pi_r(p^{cr}, e_r^{cr})$ *achieve their maximum profits.*

For the non-cooperation model, part (1) of Proposition 5 means that, in each power structure, enhancing a firm's spillover will increase the manufacturer's and the retailer's profits. Therefore, it is beneficial for both firms to enhance their technological spillovers. Recalling Lemma 2, an enhanced spillover will encourage firms to invest more in green R&D and further reduce their carbon emissions, thereby improving both economic and environmental performance.

For the cooperation model, part (2) of Proposition 5 implies that, in each power structure, if a firm's spillover is enhanced, then both its partner and the supply chain overall will gain more profits; consequently, each firm seeks the enhancement of its partner's spillover. This is different in the non-cooperation model scenario, in which both firms are willing to enhance their spillover. This finding is in line with Ge et al. (2014), who observed that, economically, the enhancement of each firm's spillover always benefits its partner and the supply chain overall. It is even more important to fairly distribute the extra profits derived from the cooperation. Otherwise, there is no incentive for firms to increase their own technological spillover, and the whole supply chain will suffer in the long run.

Part (3) of Proposition 5 represents that, for the cooperation model, the spillover's effect on each firm's own profit is more complex. More specifically, if the green contribution level difference between the manufacturer and retailer is high in the MS power structure ($G_m - G_r > \frac{2}{9}$), if the manufacturer's green contribution level is higher than the retailer's in the VN power structure ($G_m > G_r$), or if the green contribution level difference between the retailer and manufacturer is high in the

RS power structure ($G_r - G_m > \frac{2}{9}$), then the retailer's profit increases in its spillover but the manufacturer's profit decreases in its spillover. Therefore, the manufacturer is incentivised to decrease its spillover and the retailer is incentivised to increase its spillover until their green contribution level difference reaches the corresponding threshold ($G_m - G_r = \frac{2}{9}$ for MS; $G_m = G_r$ for VN; $G_r - G_m > \frac{2}{9}$ for RS).

On the contrary, if the green contribution level difference between the manufacturer and retailer is low in the MS power structure ($G_m - G_r < \frac{2}{9}$), if the manufacturer's green contribution level is lower than the retailer's in the VN power structure ($G_m < G_r$), or if the green contribution level difference between the retailer and manufacturer is low in the RS power structure ($G_r - G_m < \frac{2}{9}$), then the retailer's profit decreases in its spillover but the manufacturer's profit increases in its spillover. Therefore, the manufacturer is incentivised to increase its spillover and the retailer is incentivised to decrease its spillover until their green contribution level difference reaches the corresponding threshold ($G_m - G_r = \frac{2}{9}$ for MS; $G_m = G_r$ for VN; $G_r - G_m = \frac{2}{9}$ for RS). At this point, the manufacturer and retailer both achieve their maximum profits. We refer to the threshold as the *balanced threshold*, at which firms gain the largest economic benefits from supply chain cooperation. This is in line with the finding of Ge et al. (2014), who defined the *threshold* as a critical line and claimed that no firm has any incentive to enhance its spillover at the critical line. In this case, there is no need for firms to adjust their spillovers, which leads to changes in their green contribution levels. This is in line with Corollary 1, i.e. that two firms should match their green contribution levels in the cooperation model.

From Proposition 5, we derive the following corollary:

Corollary 2: *(1) In the asymmetric power structure (MS and RS) models, when the leader has a higher green contribution level than the follower to the critical thresholds, cooperation delivers the largest economic benefits for the manufacturer and the retailer.*

(2) In the symmetric power structure (VN) model, when the manufacturer's and retailer's green contribution levels are equal, cooperation delivers the largest economic benefits for both the manufacturer and the retailer.

5.3 The effects of spillover on customers and the environment

Regarding the effects of spillover on customers and the environment, we have the following proposition:

Proposition 6: E^{nj}, E^{cj}, CS^{nj}, CS^{cj}, SW^{nj}, *and* SW^{cj} *all increase in* θ_m *and* θ_r, *where* $j = m, v, r$.

Proposition 6 means that, in each power structure, for both the non-cooperation model and the cooperation model, if a firm's technological spillover is enhanced, then the manufacturer and retailer will invest more in green R&D, thus leading to a greater customer surplus and higher social welfare. In other words, enhancing a firm's technological spillover will benefit the environment, customers and social welfare. Therefore, it is important for supply chain firms to promote technical exchange and/or knowledge sharing between them to increase the diffusion of low carbon technology and, in turn, achieve the sustainability objectives.

6. Supply chain coordination

In this section, we focus on supply chain coordination and discuss how coordination can be achieved through two-part tariff contract payments under three different supply chain power structures (MS, VN and RS).

6.1 Integrated supply chain model

The supply chain's profit in an integrated supply chain model is:

$$\pi_t^I(e_m, p, e_r) = (p - c)[\alpha - \beta p + \gamma(e_m + e_r + \theta_m e_m + \theta_r e_r)] - \frac{1}{2}(t_m e_m^2 + t_r e_r^2) \qquad (5)$$

In the first stage, the supply chain decides on green R&D investments to maximise the supply chain's total profit. In the second stage, the supply chain decides on its retail price p to maximise the supply chain's total profit. Although the strategic and operational decisions are centralised in the integrated supply chain mode, it is logical to keep the two-stage game that the supply chain makes the centralized green R&D investment decision first, and then follows with the centralized price decision. Thus, the process of an integrated supply chain model can be described as follows:

$$\max_{e_m, e_r} \pi_t^I(e_m, p, e_r) \rightarrow \max_{p} \pi_t^I(e_m, p, e_r)$$

As to the optimal unit carbon emissions reduction of the manufacturer (e_m^I), the optimal unit carbon emissions reduction of the retailer (e_r^I) and the optimal retail price (p^I) in an integrated supply chain, the following lemma is obtained:

Lemma 3: *In an integrated supply chain,* $e_m^I = \frac{\gamma q_0(1+\theta_m)}{2t_m\beta(1-2G_m-2G_r)}$, $e_r^I = \frac{\gamma q_0(1+\theta_r)}{2t_r\beta(1-2G_m-2G_r)}$ *and* $p^I = c + \frac{q_0}{2\beta(1-2G_m-2G_r)}$.

This lemma means that in an integrated supply chain, there are unique optimal retail prices and optimal unit carbon emissions reductions for both manufacturers and retailers.

6.2 Two-part tariff contract model

For the two-part tariff contract model, the manufacturer's profit $\pi_m^i(w, e_m)$ is:

$$\pi_m^p(w, e_m) = (w-c)[\alpha - \beta p + \gamma(e_m + e_r + \theta_m e_m + \theta_r e_r)] - \frac{1}{2}t_m e_m^2 + M \tag{6}$$

Similarly, for the two-part tariff contract model, the retailer's profit $\pi_r(p, e_r)$ is:

$$\pi_r^p(p, e_r) = (p-w)[\alpha - \beta p + \gamma(e_m + e_r + \theta_m e_m + \theta_r e_r)] - \frac{1}{2}t_r e_r^2 - M \tag{7}$$

Regarding the supply chain coordination with the two-part tariff contract, the following proposition is obtained:

Proposition 7: *The supply chain can be coordinated with the two-part tariff contract, and the condition satisfies* $w = c$ *and* $M^m = \frac{\left(6-15G_r-12G_m^2G_r+6G_r^2-4G_m\left(2-5G_r+2G_r^2\right)\right)q_0^2}{8\beta(-2+2G_m+G_r)^2(-1+2G_m+2G_r)^2}$ *in the MS power structure,* $M^v = \frac{(81-96G_m^2-274G_r+224G_r^2+2G_m(-7+64G_r))q_0^2}{8\beta(-1+2G_m+2G_r)^2(-9+8G_m+8G_r)^2}$ *in the VN power structure and* $M^r = \frac{(2(1-2G_r)^2+G_m^2(-4+8G_r)+G_m(7-12G_r+12G_r^2))q_0^2}{8\beta(-2+G_m+2G_r)^2(-1+2G_m+2G_r)^2}$ *in the RS power structure.*

This proposition shows that two-part tariff contracts can coordinate the supply chain and achieve *Pareto improvement*. It demonstrates that the manufacturer and retailer can earn more profits than those without the supply chain coordination. Under the contract, the manufacturer undertakes investment in green technology and generates revenue from product sales as well as a lump-sum payment from the retailer. The retailer provides this lump-sum payment to compensate the manufacturer's green R&D investment in order to achieve the supply chain coordination. The two-part tariff contract ensures both parties can benefit from the extra profits derived from the green R&D investment cooperation. The optimal amount of this lump-sum payment is determined by a combination of factors including the price sensitivity (β) and the green contribution level of the manufacturer and retailer (G_m, G_r). It varies among different supply chain power structures.

Regarding the effect of power structure on the lump-sum payment (M), the following Corollary is obtained:

Corollary 3: $M^m > M^v > M^r$

This corollary indicates that the supply chain power relationship has a significant impact on the retailer's lump-sum payment to the manufacturer. In the MS power structure, a higher lump-sum payment will be paid to the manufacturer. In contrast, in the RS power structure, a lower lump-sum payment will be paid to the manufacturer. It shows that while both the manufacturer and retailer can gain benefit from the extra profits derived from the cooperation, the extent of this financial gain is influenced by the supply chain power relationship. In the two-part tariff contract, to meet the coordination condition $w = c$, the retailer takes all the profits, and the profit gain needs to be redistributed to the manufacturer to achieve coordination. The manufacturer or retailer will benefit from the Stackelberg leader position in the negotiation of the two-part tariff contract to splice a large portion of an extended business pie. This finding is in line with that of existing literature (Touboulic et al., 2014; Chen et al., 2017b)—i.e. that a dominant power enables firms to gain financial advantage in a contract negotiation with weaker supplier chain partners. Therefore, it is more likely in the balanced supply chain power structure that the extra profits derived from the green R&D investment cooperation can be fairly distributed among the supply chain parties.

7 Conclusion

This research investigated a supply chain in which the manufacturer and retailer first cooperate to invest in green R&D and then organise production under a wholesale price contract. Through a comparison with non-cooperation models, we focused on evaluating the effect of green R&D cooperation on the supply chain's economic, environmental and social performances. We also explored how technology spillover affects supply chain firms' strategic decision regarding green R&D cooperation, as well as the supply chain's sustainability performance. We systematically analysed these research problems in three supply chain power structures to examine the moderating effect of the power relationship on the effects of green R&D cooperation and spillover. Under the same setting, we discussed how the supply chain can be coordinated through a two-part tariff contract.

Our main research findings are as follows: First, green R&D cooperation between supply chain members will positively impact the environment, customer surplus and social welfare. Second, its impact on the supply chain's economic performance is much more complicated. It is mainly determined by each firm's own green contribution level, which is dependent on its green R&D investment efficiency, spillover and power relationship with its supply chain partners. We also show that, under each supply chain power structure, there exists a Pareto improvement region in which green R&D cooperation positively impacts all firms in the supply chain, customers and the environment. The supply chain power relationship, each firm's own green contribution level and how that level compares to that of its partners also influence this decision region. In the situation that green R&D cooperation increases the total profit for the whole supply chain but not the manufacturer or retailer, the supply chain can be coordinated through the two-part tariff contract.

7.1 Research contribution

This study makes several contributions. First, our research contributes to the green supply chain literature (Dai et al. 2017; Xu et al. 2017) by providing a better understanding of how green R&D investment cooperation can contribute to the low-carbon supply chain. Our systematic examination, in a structured manner, provides supply chain firms with strategic guidance on whether and how to engage green R&D investment cooperation with supply chain partners considering their relevant green contribution level, technological spillover and power structure. Second, our research complements the technology cooperation literature by extending its applications to the context of low carbon supply chain management (Ge et al. 2014; Luo et al. 2016; Yenipazarli 2007). We argue that a sustainable cooperative relationship requires an improvement in both economic and environmental performance as well as a fair distribution of financial benefit gained from green R&D cooperation delivering a win-win-win outcome for the environment, individual firms and consumers. Finally, our research also makes important contribution to the supply chain power relationship literature (Touboulic et al. 2014; Chen and Wang 2015; Chen et al. 2007b) by extending the application to the context of low carbon supply chain management. Our systematic examination evidently illustrates the influence of supply chain power structure on how green R&D investment cooperation impacts on supply chain firms' financial and environmental performance.

7.2 Managerial and policy implications

The results obtained from our study have important managerial and policy implications. From firms' perspective, our research findings provide clear strategic guidance on making appropriate green R&D cooperation decisions. The findings should be taken into consideration when a firm is either approached by supply chain partners or actively seeks the right cooperation partners. For instance, our research finding outlines the balanced thresholds, at which, supply chain firms can gain the largest economic benefits from green R&D cooperation under different power structures. Moreover, we also specify how technological spillover affects supply chain firms' financial performance individually and collectively under the green R&D cooperation. Regardless of industry giants or small firms with green credentials, our findings can help firms make optimal strategic and operational decisions to maximise financial benefits and positively impact the environment and customers.

However, reducing greenhouse gas emissions to tackle climate change is not only a task for commercial firms: It also requires global cooperation involving every country and all countries and their citizens. From governments' perspective, policies should be developed to incentivise industry leaders with advanced green technological capabilities to cooperate with their domestic and international supply chain partners on green technology R&D. For instance, policymakers could establish a special green fund that provides easier access to finances for supply chain firms cooperating on green R&D and innovations. Furthermore, our results show that enhancing technological spillover of supply chain firms will benefit the environment and social welfare. Policymakers should develop policies that promote technical exchange and knowledge sharing between supply chain firms to enhance low carbon technology diffusion and, in turn, support low carbon economy. Finally, as regulators, policymakers should also contribute to fair distribution of the financial benefits gained from green cooperation among the supply chain parties since it is essential to sustain such a cooperative relationship.

7.3 Future research directions

There are several research directions to build on this study. First, this research only considers a simple supply chain setting of one manufacturer and one retailer. Many supply chains consist of more than two players. It would be interesting to examine how the additional dimensions of competition among multiple players affect firms' behaviour engagement in green R&D cooperation. Second, it would be valuable to incorporate demand uncertainty in modelling firms' cooperation behaviour, as firms' decisions on cooperation are influenced by market uncertainty. Furthermore, the green R&D cooperation may be a large project, which requires considerable investment. The short-term profit gain from unit carbon emission reduction may not make up for such a high cost. In addition to technological spillover, there are some other long-term benefits such as innovation capability and market share that can make up high cost of green R&D investment in long term. One future research direction is to consider other long term effects of green R&D in the modelling. Moreover, although both firms can gain financial benefit from the green R&D cooperation through centralized investment decision or the two-part tariff contract, it is also important to ensure the gained benefit is fairly distributed between the cooperative parties. The importance of fairness issues in resource allocation/distribution has been well documented and studied in various settings (Bertsimas et al. 2011; Ho et al. 2014; Zhou et al. 2016). One future research extension is to incorporate fairness schemes such as max-min fairness and proportional fairness (Bertsimas et al. 2011) in the model to ensure fair distribution of the gained benefit. Finally, as governments around the world have widely implemented different carbon emissions control policies (e.g. carbon taxation; cap and trade), it would be useful to study the impact of different policies on firms' green R&D cooperation behaviour and the consequential sustainability performance of the supply chain.

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Appendix

Derivation of Table 2: (1) Non-cooperation model: 1) MS non-cooperation model: From Equation (2), we obtain $\frac{d^2\pi_r(p,e_r)}{dp^2} = -2\beta < 0$, so $\pi_r(p,e_r)$ is a concave function of p. Let $\frac{d\pi_r(p,e_r)}{dp} = 0$, we obtain $p = \frac{\alpha+w\beta+\gamma(e_r+e_m+e_r\theta_r+e_m\theta_m)}{2\beta}$. Replace $p = \frac{\alpha+w\beta+\gamma(e_r+e_m+e_r\theta_r+e_m\theta_m)}{2\beta}$ in $\pi_m(w,e_m)$, we obtain $\frac{d^2\pi_m(w,e_m)}{dw^2} = -\beta < 0$, so $\pi_m(w,e_m)$ is a concave function of w. Let $\frac{d\pi_m(w,e_m)}{dw} = 0$, we obtain $w = \frac{\alpha+c\beta+\gamma(e_r+e_m+e_r\theta_r+e_m\theta_m)}{2\beta}$. Replace $w = \frac{\alpha+c\beta+\gamma(e_r+e_m+e_r\theta_r+e_m\theta_m)}{2\beta}$ and $p = \frac{\alpha+w\beta+\gamma(e_r+e_m+e_r\theta_r+e_m\theta_m)}{2\beta}$ in $\pi_r(p,e_r)$ and $\pi_m(w,e_m)$, we obtain $\frac{d^2\pi_r(p,e_r)}{de_r^2} = -t_r + \frac{\gamma^2(1+\theta_r)^2}{8\beta}$, and $\frac{d^2\pi_m(w,e_m)}{de_m^2} = -t_m + \frac{\gamma^2(1+\theta_m)^2}{4\beta}$. Set $-t_m + \frac{\gamma^2(1+\theta_m)^2}{4\beta} < 0$ and $-t_r + \frac{\gamma^2(1+\theta_r)^2}{8\beta} < 0$, we obtain $G_m < 1$ and $G_r < 2$, where $G_m = \frac{\gamma^2(1+\theta_m)^2}{4t_m\beta}$ and $G_r = \frac{\gamma^2(1+\theta_r)^2}{4t_r\beta}$. So $\pi_m(w,e_m)$ is a concave function of e_m and $\pi_r(p,e_r)$ is a function of e_r. Let $\frac{d\pi_r(p,e_r)}{de_r} = \frac{d\pi_m(w,e_m)}{de_m} = 0$, we obtain $e_m^{nm} = \frac{q_0\gamma(1+\theta_m)}{2t_m\beta(2-2G_m-G_r)}$ and $e_r^{nm} = \frac{q_0\gamma(1+\theta_r)}{4t_r\beta(2-2G_m-G_r)}$. Replace e_m^{nm} and e_r^{nm} in $p = \frac{3\alpha+c\beta+3\gamma(e_r+e_m+e_r\theta_r+e_m\theta_m)}{4\beta}$ and $w = \frac{\alpha+c\beta+\gamma(e_r+e_m+e_r\theta_r+e_m\theta_m)}{2\beta}$, we obtain $w^{nm} = c + \frac{q_0}{\beta(2-2G_m-G_r)}$ and $p^{nm} = w^{nm} + \frac{q_0}{2\beta(2-2G_m-G_r)}$. Replace e_m^{nm}, e_r^{nm}, and p^{nm} in $q = \alpha - \beta p + \gamma(e_m + e_r + \theta_m e_m + \theta_r e_r)$, we obtain $q^{nm} = \frac{2q_0}{2-2G_m-G_r}$.

2) VN non-cooperation model: From Equations (1) and (2), we obtain $\frac{d^2\pi_m(w,e_m)}{dw^2} = -2\beta < 0$, and $\frac{d^2\pi_r(p,e_r)}{dp^2} = -2\beta < 0$, then $\pi_m(w,e_m)$ is a concave function of w and $\pi_r(p,e_r)$ is a concave function of p. Let $\frac{d\pi_m(w,e_m)}{dw} = \frac{d\pi_r(p,e_r)}{dp} = 0$, we obtain $w = \frac{\alpha+2c\beta+\gamma(e_r+e_m+e_r\theta_r+e_m\theta_m)}{3\beta}$ and $p = \frac{2\alpha+c\beta+2\gamma(e_r+e_m+e_r\theta_r+e_m\theta_m)}{3\beta}$. Replace $w = \frac{\alpha+2c\beta+\gamma(e_r+e_m+e_r\theta_r+e_m\theta_m)}{3\beta}$ and $p = \frac{2\alpha+c\beta+2\gamma(e_r+e_m+e_r\theta_r+e_m\theta_m)}{3\beta}$ in $\pi_r(p,e_r)$ and $\pi_m(w,e_m)$, we obtain $\frac{d^2\pi_r(p,e_r)}{de_r^2} = -t_r + \frac{2\gamma^2(1+\theta_r)^2}{9\beta}$, and $\frac{d^2\pi_m(w,e_m)}{de_m^2} = -t_m + \frac{2\gamma^2(1+\theta_m)^2}{9\beta}$. Set $-t_m + \frac{2\gamma^2(1+\theta_m)^2}{9\beta} < 0$ and $-t_r + \frac{2\gamma^2(1+\theta_r)^2}{9\beta} < 0$, we obtain $G_m < \frac{9}{8}$ and $G_r < \frac{9}{8}$, where $G_m = \frac{\gamma^2(1+\theta_m)^2}{4t_m\beta}$ and $G_r = \frac{\gamma^2(1+\theta_r)^2}{4t_r\beta}$. So $\pi_m(w,e_m)$ is a concave function of e_m and $\pi_r(p,e_r)$ is a function of e_r. Let $\frac{d\pi_r(p,e_r)}{de_r} = \frac{d\pi_m(w,e_m)}{de_m} = 0$, we obtain $e_m^{nv} = \frac{2q_0\gamma(1+\theta_m)}{t_m\beta(9-8G_m-8G_r)}$ and $e_r^{nv} = \frac{2q_0\gamma(1+\theta_r)}{t_r\beta(9-8G_m-8G_r)}$. Replace e_m^{nv} and e_r^{nv} in $w = \frac{\alpha+2c\beta+\gamma(e_r+e_m+e_r\theta_r+e_m\theta_m)}{3\beta}$ and $p = \frac{2\alpha+c\beta+2\gamma(e_r+e_m+e_r\theta_r+e_m\theta_m)}{3\beta}$, we obtain $w^{nv} = c + \frac{3q_0}{\beta(9-8G_m-8G_r)}$ and

$p^{nv} = w^{nv} + \frac{3q_0}{\beta(9-8G_m-8G_r)}$. Replace e_m^{nv}, e_r^{nv} and p^{nv} in $q = \alpha - \beta p + \gamma(e_m + e_r + \theta_m e_m + \theta_r e_r)$, we obtain $q^{nv} = \frac{3q_0}{9-8G_m-8G_r}$.

3) RS non-cooperation model: Assuming that the retailer's marginal profit is m, then $p = w + m$. Replace $p = w + m$ in Equation (1), we obtain $\pi_m(w, e_m) = (w - c)[\alpha - \beta(w + m) + \gamma(e_m + e_r + \theta_m e_m + \theta_r e_r)] - \frac{1}{2} t_m e_m^2$, then $\frac{d^2\pi_m(w,e_m)}{dw^2} = -2\beta < 0$, so $\pi_m(w, e_m)$ is a concave function of w. Let $\frac{d\pi_m(w,e_m)}{dw} = 0$, we obtain $w = \frac{\alpha+c\beta-p\beta+\gamma(e_m+e_r+\theta_m e_m+\theta_r e_r)}{\beta}$. Replace $w = \frac{\alpha+c\beta-p\beta+\gamma(e_m+e_r+\theta_m e_m+\theta_r e_r)}{\beta}$ in $\pi_r(p, e_r)$, we obtain $\frac{d^2\pi_r(p,e_r)}{dp^2} = -4\beta < 0$, so $\pi_r(p, e_r)$ is a concave function of p. Let $\frac{d\pi_r(p,e_r)}{dp} = 0$, we obtain $p = \frac{3\alpha+c\beta+3\gamma(e_m+e_r+\theta_m e_m+\theta_r e_r)}{4\beta}$. Replace $p = \frac{3\alpha+c\beta+3\gamma(e_m+e_r+\theta_m e_m+\theta_r e_r)}{4\beta}$ in $w = \frac{\alpha+c\beta-p\beta+\gamma(e_m+e_r+\theta_m e_m+\theta_r e_r)}{\beta}$, we obtain $w = \frac{\alpha+3c\beta+\gamma(e_m+e_r+\theta_m e_m+\theta_r e_r)}{4\beta}$. Replace $w = \frac{\alpha+3c\beta+\gamma(e_m+e_r+\theta_m e_m+\theta_r e_r)}{4\beta}$ and $p = \frac{3\alpha+c\beta+3\gamma(e_m+e_r+\theta_m e_m+\theta_r e_r)}{4\beta}$ in $\pi_r(p, e_r)$ and $\pi_m(w, e_m)$, we obtain $\frac{d^2\pi_r(p,e_r)}{de_r^2} = -t_r + \frac{\gamma^2(1+\theta_r)^2}{4\beta}$, and $\frac{d^2\pi_m(w,e_m)}{de_m^2} = -t_m + \frac{\gamma^2(1+\theta_m)^2}{8\beta}$. Set $-t_r + \frac{\gamma^2(1+\theta_r)^2}{4\beta} < 0$ and $-t_m + \frac{\gamma^2(1+\theta_m)^2}{8\beta} < 0$, we obtain $G_r < 1$ and $G_m < 2$, where $G_m = \frac{\gamma^2(1+\theta_m)^2}{4t_m\beta}$ and $G_r = \frac{\gamma^2(1+\theta_r)^2}{4t_r\beta}$, so $\pi_m(w, e_m)$ is a concave function of e_m and $\pi_r(p, e_r)$ is a function of e_r. Let $\frac{d\pi_r(p,e_r)}{de_r} = \frac{d\pi_m(w,e_m)}{de_m} = 0$, we obtain $e_m^{nr} = \frac{q_0\gamma(1+\theta_m)}{4t_m\beta(2-G_m-2G_r)}$ and $e_r^{nr} = \frac{q_0\gamma(1+\theta_r)}{2t_r\beta(2-G_m-2G_r)}$. Replace e_m^{nr} and e_r^{nr} in $w = \frac{\alpha+3c\beta+\gamma(e_m+e_r+\theta_m e_m+\theta_r e_r)}{4\beta}$ and $p = \frac{3\alpha+c\beta+3\gamma(e_m+e_r+\theta_m e_m+\theta_r e_r)}{4\beta}$, we obtain $w^{nr} = c + \frac{q_0}{2\beta(2-G_m-2G_r)}$ and $p^{nr} = w^{nr} + \frac{q_0}{\beta(2-G_m-2G_r)}$. Replace e_m^{nr}, e_r^{nr} and p^{nr} in $q = \alpha - \beta p + \gamma(e_m + e_r + \theta_m e_m + \theta_r e_r)$, we obtain $q^{nr} = \frac{2q_0}{2-G_m-2G_r}$.

(2) Cooperation model: 1) MS cooperation model: Replace $p = \frac{3\alpha+c\beta+3\gamma(e_r+e_m+e_r\theta_r+e_m\theta_m)}{4\beta}$ and $w = \frac{\alpha+c\beta+\gamma(e_r+e_m+e_r\theta_r+e_m\theta_m)}{2\beta}$ in $\pi_t^c(e_m, p, e_r)$, we obtain $\frac{\partial\pi_t^{c^2}(e_m,p,e_r)}{\partial e_r^2} = \frac{-8t_r\beta+3\gamma^2(1+\theta_r)^2}{8\beta}$, $\frac{\partial\pi_t^{c^2}(e_m,p,e_r)}{\partial e_m^2} = \frac{-8t_m\beta+3\gamma^2(1+\theta_m)^2}{8\beta}$, and $\frac{\partial\pi_t^{c^2}(e_m,p,e_r)}{\partial e_r\partial e_m} = \frac{\partial\pi_t^{c^2}(e_m,p,e_r)}{\partial e_m\partial e_r} = \frac{3\gamma^2(1+\theta_r)(1+\theta_m)}{8\beta}$, then $\begin{vmatrix} \frac{\partial\pi_t^{c^2}(e_m,p,e_r)}{\partial e_m^2} & \frac{\partial\pi_t^{c^2}(e_m,p,e_r)}{\partial e_r\partial e_m} \\ \frac{\partial\pi_t^{c^2}(e_m,p,e_r)}{\partial e_m\partial e_r} & \frac{\partial\pi_t^{c^2}(e_m,p,e_r)}{\partial e_r^2} \end{vmatrix} = \frac{-3t_m\gamma^2(1+\theta_r)^2+t_r(8t_m\beta-3\gamma^2(1+\theta_m)^2)}{8\beta}$. Set $\frac{-8t_m\beta+3\gamma^2(1+\theta_m)^2}{8\beta} < 0$ and $\frac{-3t_m\gamma^2(1+\theta_r)^2+t_r(8t_m\beta-3\gamma^2(1+\theta_m)^2)}{8\beta} > 0$, we obtain $G_m + G_r < \frac{2}{3}$, where $G_m = \frac{\gamma^2(1+\theta_m)^2}{4t_m\beta}$ and $G_r = \frac{\gamma^2(1+\theta_r)^2}{4t_r\beta}$. So, $\pi_t^c(e_m, p, e_r)$ is a joint concave function of e_r and e_m. Let $\frac{\partial\pi_t^c(e_m,p,e_r)}{\partial e_r} = \frac{\partial\pi_t^c(e_m,p,e_r)}{\partial e_m} = 0$, we obtain $e_m^{cm} = \frac{3q_0\gamma(1+\theta_m)}{4t_m\beta(2-3G_m-3G_r)}$ and $e_r^{cm} =$

$\frac{3q_0\gamma(1+\theta_r)}{4t_r\beta(2-3G_m-3G_r)}$. Replace e_m^{cm} and e_r^{cm} in $p=\frac{3\alpha+c\beta+3\gamma(e_r+e_m+e_r\theta_r+e_m\theta_m)}{4\beta}$ and $w=\frac{\alpha+c\beta+\gamma(e_r+e_m+e_r\theta_r+e_m\theta_m)}{2\beta}$, we obtain $w^{cm}=c+\frac{q_0}{\beta(2-3G_m-3G_r)}$ and $p^{cm}=w^{cm}+\frac{q_0}{2\beta(2-3G_m-3G_r)}$. Replace e_m^{cm}, e_r^{cm} and p^{cm} in $q=\alpha-\beta p+\gamma(e_m+e_r+\theta_m e_m+\theta_r e_r)$, we obtain $q^{cm}=\frac{2q_0}{2-3G_m-3G_r}$. 2) VN cooperation model: Replace $w=\frac{\alpha+2c\beta+\gamma(e_r+e_m+e_r\theta_r+e_m\theta_m)}{3\beta}$ and $p=\frac{2\alpha+c\beta+2\gamma(e_r+e_m+e_r\theta_r+e_m\theta_m)}{3\beta}$ in $\pi_t^c(e_m,p,e_r)$, we obtain $\frac{\partial\pi_t^{c^2}(e_m,p,e_r)}{\partial e_r^2}=\frac{-9t_r\beta+4\gamma^2(1+\theta_r)^2}{9\beta}$, $\frac{\partial\pi_t^{c^2}(e_m,p,e_r)}{\partial e_m^2}=\frac{-9t_m\beta+4\gamma^2(1+\theta_m)^2}{9\beta}$, and $\frac{\partial\pi_t^{c^2}(e_m,p,e_r)}{\partial e_r\partial e_m}=\frac{\partial\pi_t^{c^2}(e_m,p,e_r)}{\partial e_m\partial e_r}=\frac{4\gamma^2(1+\theta_r)(1+\theta_m)}{9\beta}$, then $\begin{vmatrix}\frac{\partial\pi_t^{c^2}(e_m,p,e_r)}{\partial e_m^2} & \frac{\partial\pi_t^{c^2}(e_m,p,e_r)}{\partial e_r\partial e_m}\\ \frac{\partial\pi_t^{c^2}(e_m,p,e_r)}{\partial e_m\partial e_r} & \frac{\partial\pi_t^{c^2}(e_m,p,e_r)}{\partial e_r^2}\end{vmatrix}=\frac{-4t_m\gamma^2(1+\theta_r)^2+t_r(9t_m\beta-4\gamma^2(1+\theta_m)^2)}{9\beta}$. Set $\frac{-9t_m\beta+4\gamma^2(1+\theta_m)^2}{9\beta}<0$ and $\frac{-4t_m\gamma^2(1+\theta_r)^2+t_r(9t_m\beta-4\gamma^2(1+\theta_m)^2)}{9\beta}>0$, we obtain $G_m+G_r<\frac{9}{16}$, where $G_m=\frac{\gamma^2(1+\theta_m)^2}{4t_m\beta}$ and $G_r=\frac{\gamma^2(1+\theta_r)^2}{4t_r\beta}$, so $\pi_t^c(e_m,p,e_r)$ is a joint concave function of e_r and e_m. Let $\frac{\partial\pi_t^c(e_m,p,e_r)}{\partial e_r}=\frac{\partial\pi_t^c(e_m,p,e_r)}{\partial e_m}=0$, we obtain $e_m^{cv}=\frac{4q_0\gamma(1+\theta_m)}{t_m\beta(9-16G_m-16G_r)}$ and $e_r^{cv}=\frac{4q_0\gamma(1+\theta_r)}{t_r\beta(9-16G_m-16G_r)}$. Replace e_m^{cv} and e_r^{cv} in $w=\frac{\alpha+2c\beta+\gamma(e_r+e_m+e_r\theta_r+e_m\theta_m)}{3\beta}$ and $p=\frac{2\alpha+c\beta+2\gamma(e_r+e_m+e_r\theta_r+e_m\theta_m)}{3\beta}$, we obtain $w^{cv}=c+\frac{3q_0}{\beta(9-16G_m-16G_r)}$ and $p^{cv}=w^{cv}+\frac{3q_0}{\beta(9-16G_m-16G_r)}$. Replace e_m^{cv}, e_r^{cv} and p^{cv} in $q=\alpha-\beta p+\gamma(e_m+e_r+\theta_m e_m+\theta_r e_r)$, we obtain $q^{cv}=\frac{3q_0}{9-16G_m-16G_r}$. 3) RS cooperation model: Replace $w=\frac{\alpha+3c\beta+\gamma(e_m+e_r+\theta_m e_m+\theta_r e_r)}{4\beta}$ and $p=\frac{3\alpha+c\beta+3\gamma(e_m+e_r+\theta_m e_m+\theta_r e_r)}{4\beta}$ in $\pi_t^c(e_m,p,e_r)$, we obtain $\frac{\partial\pi_t^{c^2}(e_m,p,e_r)}{\partial e_r^2}=\frac{-8t_r\beta+3\gamma^2(1+\theta_r)^2}{8\beta}$, $\frac{\partial\pi_t^{c^2}(e_m,p,e_r)}{\partial e_m^2}=\frac{-8t_m\beta+3\gamma^2(1+\theta_m)^2}{8\beta}$, and $\frac{\partial\pi_t^{c^2}(e_m,p,e_r)}{\partial e_r\partial e_m}=\frac{\partial\pi_t^{c^2}(e_m,p,e_r)}{\partial e_m\partial e_r}=\frac{3\gamma^2(1+\theta_r)(1+\theta_m)}{8\beta}$, then $\begin{vmatrix}\frac{\partial\pi_t^{c^2}(e_m,p,e_r)}{\partial e_m^2} & \frac{\partial\pi_t^{c^2}(e_m,p,e_r)}{\partial e_r\partial e_m}\\ \frac{\partial\pi_t^{c^2}(e_m,p,e_r)}{\partial e_m\partial e_r} & \frac{\partial\pi_t^{c^2}(e_m,p,e_r)}{\partial e_r^2}\end{vmatrix}=\frac{-3t_m\gamma^2(1+\theta_r)^2+t_r(8t_m\beta-3\gamma^2(1+\theta_m)^2)}{8\beta}$. Set $\frac{-8t_m\beta+3\gamma^2(1+\theta_m)^2}{8\beta}<0$ and $\frac{-3t_m\gamma^2(1+\theta_r)^2+t_r(8t_m\beta-3\gamma^2(1+\theta_m)^2)}{8\beta}>0$, we obtain $G_m+G_r<\frac{2}{3}$, where $G_m=\frac{\gamma^2(1+\theta_m)^2}{4t_m\beta}$ and $G_r=\frac{\gamma^2(1+\theta_r)^2}{4t_r\beta}$, so $\pi_t^c(e_m,p,e_r)$ is a joint concave function of e_r and e_m. Let $\frac{\partial\pi_t^c(e_m,p,e_r)}{\partial e_r}=\frac{\partial\pi_t^c(e_m,p,e_r)}{\partial e_m}=0$, we obtain $e_m^{cr}=\frac{3q_0\gamma(1+\theta_m)}{4t_m\beta(2-3G_m-3G_r)}$ and $e_r^{cr}=\frac{3q_0\gamma(1+\theta_r)}{4t_r\beta(2-3G_m-3G_r)}$. Replace e_m^{cr} and e_r^{cr} in $w=\frac{\alpha+3c\beta+\gamma(e_m+e_r+\theta_m e_m+\theta_r e_r)}{4\beta}$ and $p=\frac{3\alpha+c\beta+3\gamma(e_m+e_r+\theta_m e_m+\theta_r e_r)}{4\beta}$, we obtain $w^{cr}=c+\frac{q_0}{2\beta(2-3G_m-3G_r)}$ and $p^{cr}=w^{cr}+\frac{q_0}{\beta(2-3G_m-3G_r)}$. Replace e_m^{cr}, e_r^{cr}, and p^{cr} in $q=\alpha-\beta p+\gamma(e_m+e_r+\theta_m e_m+\theta_r e_r)$, we obtain $q^{cr}=\frac{2q_0}{2-3G_m-3G_r}$.

Proof of Lemma 1: (1) MS model: From Equation (GC), we obtain $2-3G_m-3G_r>0$. From Table 2, we obtain $T_m^c-T_m^n=\frac{q_0^2\gamma^2(8t_r\beta+3\gamma^2(1+\theta_r)^2)(1+\theta_m)^2(10-12G_m-9G_r)}{128\beta^2(2-3G_m-3G_r)^2(2-2G_m-G_r)^2}>0$, $T_r^c-T_r^n=\frac{q_0^2\gamma^2(1+\theta_r)^2(16t_m\beta-3\gamma^2(1+\theta_m)^2)(8-9G_m-6G_r)}{128\beta^2(2-3G_m-3G_r)^2(2-2G_m-G_r)^2}>0$, $e_m^c-e_m^n=\frac{(2+3G_r)q_0\gamma(1+\theta_m)}{4(2-2G_m-G_r)(2-3G_m-3G_r)t_m\beta}>0$, $e_r^c-e_r^n=\frac{(4-3G_m)q_0\gamma(1+\theta_r)}{4(2-2G_m-G_r)(2-3G_m-3G_r)t_r\beta}>0$, $w^c-w^n=\frac{(2G_r+G_m)q_0}{(2-2G_m-G_r)(2-3G_m-3G_r)\beta}>0$, $p^c-p^n=\frac{3(2G_r+G_m)q_0}{2(2-2G_m-G_r)(2-3G_m-3G_r)\beta}>0$, and $q^c-q^n=\frac{2(2G_r+G_m)q_0}{(2-2G_m-G_r)(2-3G_m-3G_r)}>0$, then $T_m^c>T_m^n$, $T_r^c>T_r^n$, $e_m^c>e_m^n$, $e_r^c>e_r^n$, $w^c>w^n$, $p^c>p^n$, and $q^c>q^n$.

(2) VN model: From Equation (GCV), we obtain $9-16G_m-16G_r>0$. From Table 2, we obtain $T_m^{cv}-T_m^{nv}=\frac{18q_0^2\gamma^2(1+\theta_m)^2(27-32G_m-32G_r)}{t_m\beta^2(9-8G_m-8G_r)^2(9-16G_m-16G_r)^2}>0$, $T_r^{cv}-T_r^{nv}=\frac{18q_0^2\gamma^2(1+\theta_r)^2(27-32G_m-32G_r)}{t_r\beta^2(9-8G_m-8G_r)^2(9-16G_m-16G_r)^2}>0$, $e_m^{cv}-e_m^{nv}=\frac{18q_0\gamma(1+\theta_m)}{(9-8G_m-8G_r)(9-16G_m-16G_r)t_m\beta}>0$, $e_r^{cv}-e_r^{nv}=\frac{18q_0\gamma(1+\theta_r)}{(9-8G_m-8G_r)(9-16G_m-16G_r)t_r\beta}>0$, $w^{cv}-w^{nv}=\frac{24(G_r+G_m)q_0}{(9-8G_m-8G_r)(9-16G_m-16G_r)\beta}>0$, $p^{cv}-p^{nv}=\frac{48(G_r+G_m)q_0}{(9-8G_m-8G_r)(9-16G_m-16G_r)\beta}>0$, and $q^{cv}-q^{nv}=\frac{24(G_r+G_m)q_0}{(9-8G_m-8G_r)(9-16G_m-16G_r)}>0$, then $T_m^{cv}>T_m^{nv}$, $T_r^{cv}>T_r^{nv}$, $e_m^{cv}>e_m^{nv}$, $e_r^{cv}>e_r^{nv}$, $w^{cv}>w^{nv}$, $p^{cv}>p^{nv}$, and $q^{cv}>q^{nv}$.

(3) RS model: From Equation (GC), we obtain $2-3G_m-3G_r>0$. From Table 2, we obtain $T_m^{cr}-T_m^{nr}=\frac{q_0^2\gamma^2(16t_r\beta-3\gamma^2(1+\theta_r)^2)(1+\theta_m)^2(8-6G_m-9G_r)}{128t_mt_r\beta^3(2-3G_m-3G_r)^2(2-G_m-2G_r)^2}>0$, $T_r^{cr}-T_r^{nr}=\frac{q_0^2\gamma^2(1+\theta_r)^2(8t_m\beta+3\gamma^2(1+\theta_m)^2)(10-9G_m-12G_r)}{128t_mt_r\beta^3(2-3G_m-3G_r)^2(2-G_m-2G_r)^2}$, $e_m^{cr}-e_m^{nr}=\frac{(4-3G_r)q_0\gamma(1+\theta_m)}{4(2-G_m-2G_r)(2-3G_m-3G_r)t_m\beta}>0$, $e_r^{cr}-e_r^{nr}=\frac{(2+3G_m)q_0\gamma(1+\theta_r)}{4(2-G_m-2G_r)(2-3G_m-3G_r)t_r\beta}>0$, $w^{cr}-w^{nr}=\frac{(G_r+2G_m)q_0}{2(2-G_m-2G_r)(2-3G_m-3G_r)\beta}>0$, $p^{cr}-p^{nr}=\frac{3(G_r+2G_m)q_0}{2(2-G_m-2G_r)(2-3G_m-3G_r)\beta}>0$, and $q^{cr}-q^{nr}=\frac{(G_r+2G_m)q_0}{2(2-G_m-2G_r)(2-3G_m-3G_r)}>0$, then $T_m^{cr}-T_m^{nr}$, $T_r^{cr}>T_r^{nr}$, $e_m^{cr}>e_m^{nr}$, $e_r^{cr}>e_r^{nr}$, $w^{cr}>w^{nr}$, $p^{cr}>p^{nr}$, and $q^{cr}>q^{nr}$.

Therefore, $T_r^{cj}>T_r^{nj}$, $T_m^{cj}>T_m^{nj}$, $e_m^{cj}>e_m^{nj}$, $e_r^{cj}>e_r^{nj}$, $w^{cj}>w^{nj}$, $p^{cj}>p^{nj}$ *and,* $q^{cj}>q^{nj}$*;* where $j=m,v,r$.

Proof of Proposition 1: From Table 2 and Equation (3), (4), we obtain $\pi_t^c(e_m^{cm},p^{cm},e_r^{cm})-\pi_t^n(w^{nm},e_m^{nm},p^{nm},e_r^{nm})=\frac{(2G_m+G_r(8-3G_m))q_0^2}{8(2-2G_m-G_r)^2(2-3G_m-3G_r)\beta}>0$, $\pi_t^c(e_m^{cv},p^{cv},e_r^{cv})-\pi_t^n(w^{nv},e_m^{nv},p^{nv},e_r^{nv})=\frac{72(G_m+G_r)q_0^2}{(9-8G_m-8G_r)^2(9-16G_m-16G_r)\beta}>0$, and $\pi_t^c(e_m^{cr},p^{cr},e_r^{cr})-\pi_t^n(w^{nr},e_m^{nr},p^{nr},e_r^{nr})=\frac{(2G_r+G_m(8-3G_r))q_0^2}{8(2-G_m-2G_r)^2(2-3G_m-3G_r)\beta}>0$, then $\pi_t^n\left(w^{nj},e_m^{nj},p^{nj},e_r^{nj}\right)$; where $j=m,v,r$.

Proof of Proposition 2: (1) MS model: From Table 2 and Equation (1), we obtain $\pi_m(w^{cm},e_m^{cm})-\pi_m(w^{nm},e_m^{nm})=\frac{q_0^2(4(1+9G_r)G_m^2+(-4-68G_r+27G_r^2)G_m+32G_r-32G_r^2)}{8(2-2G_m-G_r)^2(2-3G_m-3G_r)^2\beta}$. Set $F_1(G_m)=4(1+9G_r)G_m^2+(-4-68G_r+27G_r^2)G_m+32G_r-32G_r^2$. $4(1+9G_r)>0$ means that $F_1(G_m)$ is a convex function. $\Delta=4-4G_r+81G_r^2>$

0 means that there are two real roots for $F_1(G_m)=0$, then $G_{m1}^m=\frac{4+68G_r-27G_r^2-(2+3G_r)\sqrt{4-4G_r+81G_r^2}}{2(4+36G_r)}$ and $G_{m2}^m=\frac{4+68G_r-27G_r^2+(2+3G_r)\sqrt{4-4G_r+81G_r^2}}{2(4+36G_r)}$. From Equation (GC), we obtain $4+68G_r-27G_r^2=4+G_r(68-27G_r)>0$ and $(4+68G_r-27G_r^2)^2-(2+3G_r)^2(4-4G_r+81G_r^2)=512(1-G_r)G_r(1+9G_r)>0$, then $G_{m1}^{\mathrm{m}}>0$. $G_{m2}^m-\frac{2}{3}=\frac{-4+60G_r-81G_r^2+(6+9G_r)\sqrt{(2-G_r)^2+80G_r^2}}{2(4+36G_r)}>\frac{-4+60G_r-81G_r^2+(6+9G_r)(2-G_r)}{2(4+36G_r)}=\frac{8+G_r(78-90G_r)}{2(4+36G_r)}>0$, then $G_{m2}^m>\frac{2}{3}>G_m$. So, if $0<G_m<f_r^m(G_r)$, then $\pi_m(w^{cm},e_m^{cm})>\pi_m(w^{nm},e_m^{nm})$; if $f_r^m(G_r)<G_m<\frac{2}{3}$, then $\pi_m(w^{cm},e_m^{cm})<\pi_m(w^{nm},e_m^{nm})$; where $f_r^m(G_r)=G_{m1}^m=\frac{4+68G_r-27G_r^2-(2+3G_r)\sqrt{4-4G_r+81G_r^2}}{2(4+36G_r)}$.

(2) VN model: From Table 2 and Equation (1), we obtain $\pi_m(w^{cv},e_m^{cv})-\pi_m(w^{nv},e_m^{nv})=\frac{72(8G_m^2-G_m(9+16G_r)+6(3-4G_r)G_r)q_0^2}{(9-8G_m-8G_r)^2(9-16G_m-16G_r)^2\beta}$. Set $F_1(G_m)=8G_m^2-G_m(9+16G_r)+6(3-4G_r)G_r$, then $F_1(G_m)$ is a convex function. $\Delta=81+32G_r(-9+32G_r)>0$ means that there are two real roots for $F_1(G_m)=0$, then $G_{m1}^v=\frac{1}{16}(9+16G_r-\sqrt{81-288G_r+1024G_r^2})$ and $G_{m2}^v=\frac{1}{16}\left(9+16G_r+\sqrt{81-288G_r+1024G_r^2}\right)>G_{m1}$. From Equation (GCV), we obtain $(9+16G_r)^2-(81-288G_r+1024G_r^2)=192(3-4G_r)G_r>0$, then $G_{m1}^v>0$. $G_{m2}^v-\frac{9}{16}=\frac{1}{16}(16G_r+\sqrt{81-288G_r+1024G_r^2}>0$, then $G_{m2}^v>\frac{9}{16}>G_m$. So, if $0<G_m<f_r^v(G_r)$, then $\pi_m(w^{cv},e_m^{cv})>\pi_m(w^{nv},e_m^{nv})$; if $f_r^v(G_r)<G_m<\frac{9}{16}$, then $\pi_m(w^{cv},e_m^{cv})<\pi_m(w^{nv},e_m^{nv})$; where $f_r^v(G_r)=G_{m1}^v=\frac{9+16G_r-\sqrt{81-288G_r+1024G_r^2}}{16}$.

(3) RS model: From Table 2 and Equation (1), we obtain $\pi_m(w^{cr},e_m^{cr})-\pi_m(w^{nr},e_m^{nr})=\frac{(G_m^2(8-18G_r)+G_m(-16+32G_r-27G_r^2)+8G_r-10G_r^2)}{8(2-2G_r-G_m)^2(2-3G_r-3G_m)^2\beta}$. Set $F_1(G_m)=G_m^2(8-18G_r)+G_m(-16+32G_r-27G_r^2)+8G_r-10G_r^2$. If $0<G_r<\frac{4}{9}$, then $8-18G_r>0$ and $F_1(G_m)$ is a convex function; if $\frac{4}{9}<G_r<\frac{2}{3}$, then $8-18G_r<0$ and $F_1(G_m)$ is a concave function. $\Delta=(4-3G_r)^2\big(16+G_r(-56+81G_r)\big)>0$ means that there are two real roots for $F_1(G_m)=0$, then $G_{m1}^r=\frac{16-32G_r+27G_r^2-(4-3G_r)\sqrt{16-56G_r+81G_r^2}}{2(8-18G_r)}$ and $G_{m2}^r=\frac{16-32G_r+27G_r^2+(4-3G_r)\sqrt{16-56G_r+81G_r^2}}{2(8-18G_r)}>G_{m1}$. 1) $0<G_r<\frac{4}{9}$. $G_{m2}^r=\frac{16-32G_r+27G_r^2+(4-3G_r)\sqrt{16-56G_r+81G_r^2}}{2(8-18G_r)}>\frac{16-32G_r+27G_r^2+(4-3G_r)(4-9G_r)}{2(8-18G_r)}=\frac{32-80G_r+54G_r^2}{2(8-18G_r)}>\frac{32-96G_r+54G_r^2}{2(8-18G_r)}=2-\frac{3}{2}G_r>1>G_m$, then $G_m<\frac{2}{3}<G_{m2}^r$. $(16-32G_r+27G_r^2)^2-\left((4-3G_r)\sqrt{16-56G_r+81G_r^2}\right)^2=16G_r(4-5G_r)(4-9G_r)>0$ means that $G_{m1}^r>0$. Therefore, if $0<G_r<\frac{4}{9}$ and $0<G_m<f_r^r(G_r)$, then $\pi_m(w^{cr},e_m^{cr})>\pi_m(w^{nr},e_m^{nr})$; if $0<G_r<\frac{4}{9}$ and $f_r^r(G_r)<G_m<\frac{2}{3}$, then $\pi_m(w^{cr},e_m^{cr})<\pi_m(w^{nr},e_m^{nr})$; where $f_r^r(G_r)=G_{m1}^r=\frac{16-32G_r+27G_r^2-(4-3G_r)\sqrt{16-56G_r+81G_r^2}}{2(8-18G_r)}$. 2) $\frac{4}{9}<G_r<\frac{2}{3}$. From Equation (GC), we obtain $0<G_m<\frac{2}{9}$. $\frac{2}{9}-G_{m1}=$

$\frac{112-216G_r+243G_r^2-(36-27G_r)\sqrt{16-56G_r+81G_r^2}}{36(-4+9G_r)} > 0$, then $G_{m1}^r < \frac{2}{9}$. Therefore, if $\frac{4}{9} < G_r < \frac{2}{3}$ and $f_r^r(G_r) < G_m < \frac{2}{9}$, then $\pi_m(w^{cr}, e_m^{cr}) > \pi_m(w^{nr}, e_m^{nr})$; if $\frac{4}{9} < G_r < \frac{2}{3}$ and $0 < G_m < f_r^r(G_r)$, then $\pi_m(w^{cr}, e_m^{cr}) < \pi_m(w^{nr}, e_m^{nr})$; where $f_r^r(G_r) = G_{m1}^r = \frac{16-32G_r+27G_r^2-(4-3G_r)\sqrt{16-56G_r+81G_r^2}}{2(8-18G_r)}$.

Proof of Proposition 3: (1) MS model: From Table 2 and Equation (2), we obtain $\pi_r(p^{cm}, e_r^{cm}) - \pi_r(p^{nm}, e_r^{nm}) = \frac{q_0^2(G_r^2(8-18G_m)+G_r(-16+32G_m-27G_m^2)+8G_m-10G_m^2)}{8(2-2G_m-G_r)^2(2-3G_m-3G_r)^2\beta}$. Set $F_2(G_r) = G_r^2(8-18G_m) + G_r(-16+32G_m - 27G_m^2) + 8G_m - 10G_m^2$. If $0 < G_m < \frac{4}{9}$, then $8-18G_m > 0$ and $F_2(G_r)$ is a convex function; if $\frac{4}{9} < G_m < \frac{2}{3}$, then $8-18G_m < 0$ and $F_2(G_r)$ is a concave function. $\Delta = (4-3G_m)^2\big(16+G_m(-56+81G_m)\big) > 0$ means that there are two real roots for $F_2(G_r) = 0$, then $G_{r1}^m = \frac{16-32G_m+27G_m^2-(4-3G_m)\sqrt{16+G_m(-56+81G_m)}}{2(8-18G_m)}$ and $G_{r2}^m = \frac{16-32G_m+27G_m^2+(4-3G_m)\sqrt{16+G_m(-56+81G_m)}}{2(8-18G_m)} > G_{r1}$. 1) $0 < G_m < \frac{4}{9}$. $G_{r2}^m = \frac{16-32G_m+27G_m^2+(4-3G_m)\sqrt{16+G_m(-56+81G_m)}}{2(8-18G_m)} > \frac{16-32G_m+27G_m^2+(4-3G_m)(4-9G_m)}{2(8-18G_m)} = \frac{32-80G_m+54G_m^2}{2(8-18G_m)} > \frac{32-96G_m+54G_m^2}{2(8-18G_m)} = 2-\frac{3}{2}G_m > 1 > G_r$, then $G_r < \frac{2}{3} < G_{r2}^m$. $(16-32G_m+27G_m^2)^2 - \left((4-3G_m)\sqrt{16+G_m(-56+81G_m)}\right)^2 = 16G_m(4-5G_m)(4-9G_m) > 0$ means that $G_{r1}^m > 0$. Therefore, if $0 < G_m < \frac{4}{9}$ and $0 < G_r < f_m^m(G_m)$, then $\pi_r(p^{cm}, e_r^{cm}) > \pi_r(p^{nm}, e_r^{nm})$; if $0 < G_m < \frac{4}{9}$ and $f_m^m(G_m) < G_r < \frac{2}{3}$, then $\pi_r(p^{cm}, e_r^{cm}) < \pi_r(p^{nm}, e_r^{nm})$; where $f_m^m(G_m) = G_{r1}^m = \frac{16-32G_m+27G_m^2-(4-3G_m)\sqrt{16-56G_m+81G_m^2}}{2(8-18G_m)}$. 2) $\frac{4}{9} < G_m < \frac{2}{3}$. From Equation (GC), we obtain $0 < G_r < \frac{2}{9}$. $\frac{2}{9} - G_{r1}^m = \frac{112-216G_m+243G_m^2-(36-27G_m)\sqrt{16+G_m(-56+81G_m)}}{36(-4+9G_m)} > 0$, then $G_{r1}^m < \frac{2}{9}$. Therefore, if $\frac{4}{9} < G_m < \frac{2}{3}$ and $f_m^m(G_m) < G_r < \frac{2}{9}$, then $\pi_r(p^{cm}, e_r^{cm}) > \pi_r(p^{nm}, e_r^{nm})$; if $\frac{4}{9} < G_m < \frac{2}{3}$ and $0 < G_r < f_m^m(G_m)$, then $\pi_r(p^{cm}, e_r^{cm}) < \pi_r(p^{nm}, e_r^{nm})$; where $f_m^m(G_m) = G_{r1}^m = \frac{16-32G_m+27G_m^2-(4-3G_m)\sqrt{16-56G_m+81G_m^2}}{2(8-18G_m)}$.

(2) VN model: From Table 2 and Equation (2), we obtain $\pi_r(p^{cv}, e_r^{cv}) - \pi_r(p^{nv}, e_r^{nv}) = \frac{72(8G_r^2-G_r(9+16G_m)+6(3-4G_m)G_m)q_0^2}{(9-8G_m-8G_r)^2(9-16G_m-16G_r)^2\beta}$. Set $F_2(G_r) = 8G_r^2 - G_r(9+16G_m) + 6(3-4G_m)G_m$, then $F_2(G_r)$ is a convex function. $\Delta = 81 + 32G_m(-9+32G_m) > 0$ means that there are two real roots for $F_2(G_r) = 0$, then $G_{r1}^v = \frac{1}{16}(9+16G_m - \sqrt{81-288G_m+1024G_m^2})$ and $G_{r2}^v = \frac{1}{16}(9+16G_m+\sqrt{81-288G_m+1024G_m^2}) > G_{r1}^v$. From Equation (GCV), we obtain $(9+16G_m)^2 - (81-288G_m+1024G_m^2) = 192(3-4G_m)G_m > 0$, then $G_{r1}^v > 0$. $G_{r2}^v - \frac{9}{16} = \frac{1}{16}(16G_m + \sqrt{81-288G_m+1024G_m^2}) > 0$, then $G_{r2}^v > \frac{9}{16} > G_r$. So, if $0 < G_r <$

$f_m^v(G_m)$, then $\pi_r(p^{cv}, e_r^{cv}) > \pi_r(p^{nv}, e_r^{nv})$; if $f_m^v(G_m) < G_r < \frac{9}{16}$, then $\pi_r(p^{cv}, e_r^{cv}) < \pi_r(p^{nv}, e_r^{nv})$; where $f_m^v(G_m) = G_{r1}^v = \frac{9+16G_m-\sqrt{81-288G_m+1024G_m^2}}{16}$.

(3) RS model: From Table 2 and Equation (2), we obtain $\pi_r(p^{cr}, e_r^{cr}) - \pi_r(p^{nr}, e_r^{nr}) = \frac{q_0^2(4(1+9G_m)G_r^2+(-4-68G_m+27G_m^2)G_r+32G_m-32G_m^2)}{8(2-2G_r-G_m)^2(2-3G_r-3G_m)^2\beta}$. Set $F_2(G_r) = 4(1+9G_m)G_r^2 + (-4-68G_m+27G_m^2)G_r + 32G_m - 32G_m^2$. $4(1+9G_m) > 0$ means that $F_2(G_r)$ is a convex function. $\Delta = 4 - 4G_m + 81G_m^2 > 0$ means that there are two real roots for $F_2(G_r) = 0$, then $G_{r1}^r = \frac{4+68G_m-27G_m^2-(2+3G_m)\sqrt{4-4G_m+81G_m^2}}{2(4+36G_m)}$ and $G_{r2}^r = \frac{4+68G_m-27G_m^2+(2+3G_m)\sqrt{4-4G_m+81G_m^2}}{2(4+36G_m)}$.

From Equation (GC), we obtain $4 + 68G_m - 27G_m^2 = 4 + G_m(68 - 27G_m) > 0$ and $(4 + 68G_m - 27G_m^2)^2 - (2+3G_m)^2(4 - 4G_m + 81G_m^2) = 512(1-G_m)G_m(1+9G_m) > 0$, then $G_{r1}^r > 0$. $G_{r2}^r - \frac{2}{3} = \frac{-4+60G_m-81G_m^2+(6+9G_m)\sqrt{(2-G_m)^2+80G_m^2}}{2(4+36G_m)} > \frac{-4+60G_m-81G_m^2+(6+9G_m)(2-G_m)}{2(4+36G_m)} = \frac{8+G_m(78-90G_m)}{2(4+36G_m)} > 0$, then $G_{r2}^r > \frac{2}{3} > G_r$. So, if $0 < G_r < f_m^r(G_m)$, then $\pi_r(p^{cr}, e_r^{cr}) > \pi_r(p^{nr}, e_r^{nr})$; if $f_m^r(G_m) < G_r < \frac{2}{3}$, then $\pi_r(p^{cr}, e_r^{cr}) < \pi_r(p^{nr}, e_r^{nr})$; where $f_m^r(G_m) = G_{r1}^r = \frac{4+68G_m-27G_m^2-(2+3G_m)\sqrt{4-4G_m+81G_m^2}}{2(4+36G_m)}$.

Proof of Corollary 1: (1) MS model: $\frac{4}{9} - f_r^m(G_r) = \frac{(18+27G_r)\sqrt{4-4G_r+81G_r^2}-(4+324G_r-243G_r^2)}{72(1+9G_r)}$. Since $((18 + 27G_r)\sqrt{4-4G_r+81G_r^2})^2 - (4+324G_r-243G_r^2)^2 = 320(2-9G_r)^2(1+9G_r) > 0$, then $\frac{4}{9} > f_r^m(G_r)$. From Propositions 2 and 3, we obtain if $0 < G_m < f_r^m(G_r)$, $0 < G_m < \frac{4}{9}$, and $0 < G_r < f_m^m(G_m)$, then $\pi_r(w^{cm}, e_r^{cm}) > \pi_r(w^{nm}, e_r^{nm})$ and $\pi_m(w^{cm}, e_m^{cm}) > \pi_m(w^{nm}, e_m^{nm})$. Therefore, if $0 < G_m < f_r^m(G_r)$ and $0 < G_r < f_m^m(G_m)$, then $\pi_m(w^{cm}, e_m^{cm}) > \pi_m(w^{nm}, e_m^{nm})$ and $\pi_r(w^{cm}, e_r^{cm}) > \pi_r(w^{nm}, e_r^{nm})$.

(2) VN model: From Propositions 2 and 3, we can directly obtain that in the VN model, if $0 < G_m < f_r^v(G_r)$ and $0 < G_r < f_m^v(G_m)$, then $\pi_m(w^{cv}, e_m^{cv}) > \pi_m(w^{nv}, e_m^{nv})$ and $\pi_r(w^{cv}, e_r^{cv}) > \pi_r(w^{nv}, e_r^{nv})$.

(3) RS model: $\frac{4}{9} - f_m^r(G_m) = \frac{(18+27G_m)\sqrt{4-4G_m+81G_m^2}-(4+324G_m-243G_m^2)}{72(1+9G_m)}$. Since $((18 + 27G_m)\sqrt{4-4G_m+81G_m^2})^2 - (4+324G_m-243G_m^2)^2 = 320(2-9G_m)^2(1+9G_m) > 0$, then $\frac{4}{9} > f_m^r(G_m)$. From Propositions 2 and 3, we obtain if $0 < G_r < f_m^r(G_m)$, $0 < G_r < \frac{4}{9}$, and $0 < G_m < f_r^r(G_r)$, then $\pi_m(w^{cr}, e_m^{cr}) > \pi_m(w^{nr}, e_m^{nr})$ and $\pi_r(w^{cr}, e_r^{cr}) > \pi_r(w^{nr}, e_r^{nr})$. Therefore, if $0 < G_r < f_m^r(G_m)$ and $0 < G_m < f_r^r(G_r)$, then $\pi_m(w^{cr}, e_m^{cr}) > \pi_m(w^{nr}, e_m^{nr})$ and $\pi_r(w^{cr}, e_r^{cr}) > \pi_r(w^{nr}, e_r^{nr})$.

Proof of Proposition 4: From Equations (GC) and (GVC), we obtain $2 - 3G_m - 3G_r > 0$ and $3 - 4G_m - 4G_r > 0$. (1) Recalling $E = (e_m + e_r)q$, from Lemma 1, we can directly derive that $E^{cj} > E^{nj}$. (2) From Table 2, we obtain $CS^{cm} - CS^{nm} = \frac{(2G_r+G_m)(4-4G_r-5G_m)q_0^2}{8(2-2G_m-G_r)^2(2-3G_m-3G_r)^2\beta} > 0$, $CS^{cv} - CS^{nv} =$

$\frac{216(G_m+G_r)(3-4G_m-4G_r)q_0^2}{(9-8G_m-8G_r)^2(9-16G_m-16G_r)^2\beta} > 0$, and $CS^{cr} - CS^{nr} = \frac{(G_r+2G_m)(4-5G_r-4G_m)q_0^2}{8(2-G_m-2G_r)^2(2-3G_m-3G_r)^2\beta} > 0$, then $CS^{cj} > CS^{nj}$. (3) Recalling that $SW = CS + \pi_m(w, e_m) + \pi_r(p, e_r) + c_e E$, we can directly derive that $SW^{cj} > SW^{nj}$; where $j = m, v, r$.

Proof of Lemma 2: (1) MS model: From Equation (GC), we obtain $2 - 3G_m - 3G_r > 0$. 1) MS non-cooperation model: From Table 2, we obtain $\frac{dT_r^{nm}}{d\theta_m} = \frac{q_0^2\gamma^4(1+\theta_r)^2(1+\theta_m)}{16t_m t_r\beta^2(2-2G_m-G_r)^3} > 0$, $\frac{dT_r^{nm}}{d\theta_r} = \frac{q_0^2\gamma^2(1+\theta_r)(2-2G_m+G_r)}{64t_r\beta^2(2-2G_m-G_r)^3} > 0$, $\frac{dT_m^{nm}}{d\theta_m} = \frac{q_0^2\gamma^2(1+\theta_m)(2+2G_m-G_r)}{16t_m\beta^2(2-2G_m-G_r)^3} > 0$, $\frac{dT_m^{nm}}{d\theta_r} = \frac{q_0^2\gamma^4(1+\theta_r)(1+\theta_m)^2}{8t_m t_r\beta^2(2-2G_m-G_r)^3} > 0$, $\frac{de_m^{nm}}{d\theta_m} = \frac{q_0\gamma(2+2G_m-G_r)}{2t_m\beta(2-2G_m-G_r)^2} > 0$, $\frac{de_r^{nm}}{d\theta_m} = \frac{\gamma^3 q_0(1+\theta_r)(1+\theta_m)}{4t_r t_m\beta^2(2-2G_m-G_r)^2} > 0$, $\frac{de_m^{nm}}{d\theta_r} = \frac{\gamma^3 q_0(1+\theta_r)(1+\theta_m)}{4t_r t_m\beta^2(2-2G_m-G_r)^2} > 0$, $\frac{de_r^{nm}}{d\theta_r} = \frac{q_0\gamma(2-2G_m+G_r)}{4t_r\beta(2-2G_m-G_r)^2} > 0$, $\frac{dw^{nm}}{d\theta_m} = \frac{\gamma^2 q_0(1+\theta_m)}{t_m\beta^2((2-2G_m-G_r)^2} > 0$, $\frac{dw^{nm}}{d\theta_r} = \frac{\gamma^2 q_0(1+\theta_r)}{2t_r\beta^2(2-2G_m-G_r)^2} > 0$, $\frac{dp^{nm}}{d\theta_m} = \frac{3\gamma^2 q_0(1+\theta_m)}{2t_m\beta^2(2-2G_m-G_r)^2} > 0$, $\frac{dp^{nm}}{d\theta_r} = \frac{3\gamma^2 q_0(1+\theta_r)}{4t_r\beta^2(2-2G_m-G_r)^2} > 0$, $\frac{dq^{nm}}{d\theta_m} = \frac{q_0\gamma^2(1+\theta_m)}{2\beta t_m(2-2G_m-G_r)^2} > 0$, and $\frac{dq^{nm}}{d\theta_r} = \frac{q_0\gamma^2(1+\theta_r)}{4\beta t_r(2-2G_m-G_r)^2} > 0$, then e_m^{nm}, e_r^{nm}, w^{nm}, p^{nm}, T_r^{nm}, T_m^{nm}, and q^{nm} all increase in θ_m and θ_r. 2) MS cooperation model: From Table 2, we obtain $\frac{dT_r^{cm}}{d\theta_m} = \frac{27q_0^2\gamma^4(1+\theta_r)^2(1+\theta_m)}{32\beta^2(2-3G_m-3G_r)^3} > 0$, $\frac{dT_r^{cm}}{d\theta_r} = \frac{9q_0^2\gamma^2(1+\theta_r)(2-3G_m+3G_r)}{16t_r\beta^2(2-3G_m-3G_r)^3} > 0$, $\frac{dT_m^{cm}}{d\theta_m} = \frac{9q_0^2\gamma^2(1+\theta_m)(2+3G_m-3G_r)}{16t_m\beta^2(2-3G_m-3G_r)^3} > 0$, $\frac{dT_m^{cm}}{d\theta_r} = \frac{27q_0^2\gamma^4(1+\theta_r)(1+\theta_m)^2}{32\beta^2(2-3G_m-3G_r)^3} > 0$, $\frac{de_m^{cm}}{d\theta_m} = \frac{3\gamma q_0(2+3G_m-3G_r)}{4t_m\beta(2-3G_m-3G_r)^2} > 0$, $\frac{de_r^{cm}}{d\theta_m} = \frac{9\gamma^3 q_0(1+\theta_r)(1+\theta_m)}{8\beta^2 t_r t_m(2-3G_m-3G_r)^2} > 0$, $\frac{de_m^{cm}}{d\theta_r} = \frac{9\gamma^3 q_0(1+\theta_r)(1+\theta_m)}{8\beta^2 t_r t_m(2-3G_m-3G_r)^2} > 0$, $\frac{de_r^{cm}}{d\theta_r} = \frac{3\gamma q_0(2-3G_m+3G_r)}{4t_r\beta(2-3G_m-3G_r)^2} > 0$, $\frac{dw^{cm}}{d\theta_m} = \frac{3\gamma^2 q_0(1+\theta_m)}{2t_m\beta^2(2-3G_m-3G_r)^2} > 0$, $\frac{dw^{cm}}{d\theta_r} = \frac{3\gamma^2 q_0(1+\theta_r)}{2t_r\beta^2(2-3G_m-3G_r)^2} > 0$, $\frac{dp^{cm}}{d\theta_m} = \frac{9\gamma^2 q_0(1+\theta_m)}{4t_m\beta^2(2-3G_m-3G_r)^2} > 0$, $\frac{dp^{cm}}{d\theta_r} = \frac{9\gamma^2 q_0(1+\theta_r)}{4t_r\beta^2(2-3G_m-3G_r)^2} > 0$, $\frac{dq^{cm}}{d\theta_m} = \frac{3q_0\gamma^2(1+\theta_m)}{4\beta t_m(2-3G_m-3G_r)^2} > 0$, and $\frac{dq^{cm}}{d\theta_r} = \frac{3q_0\gamma^2(1+\theta_r)}{4\beta t_r(2-3G_m-3G_r)^2} > 0$, then e_m^{cm}, e_r^{cm}, w^{cm}, p^{cm}, T_r^{cm}, T_m^{cm}, and q^{cm} all increase in θ_m and θ_r.

(2) VN model: From Equation (GCV), we obtain $9 - 16G_m - 16G_r > 0$. 1) VN non-cooperation model: From Table 2, we obtain $\frac{dT_r^{nv}}{d\theta_m} = \frac{16q_0^2\gamma^4(1+\theta_r)^2(1+\theta_m)}{t_m t_r\beta^3(9-8G_m-8G_r)^3} > 0$, $\frac{dT_r^{nv}}{d\theta_r} = \frac{4q_0^2\gamma^2(1+\theta_r)(9-8G_m+8G_r)}{t_r\beta^3(9-8G_m-8G_r)^3} > 0$, $\frac{dT_m^{nv}}{d\theta_m} = \frac{4q_0^2\gamma^2(1+\theta_m)(9+8G_m-8G_r)}{t_m\beta^3(9-8G_m-8G_r)^3} > 0$, $\frac{dT_m^{nv}}{d\theta_r} = \frac{16q_0^2\gamma^4(1+\theta_r)(1+\theta_m)^2}{t_m t_r\beta^3(9-8G_m-8G_r)^3} > 0$, $\frac{de_m^{nv}}{d\theta_m} = \frac{2q_0\gamma(9+8G_m-8G_r)}{t_m\beta(9-8G_m-8G_r)^2} > 0$, $\frac{de_r^{nv}}{d\theta_m} = \frac{8\gamma^3 q_0(1+\theta_r)(1+\theta_m)}{t_r t_m\beta^2(9-8G_m-8G_r)^2} > 0$, $\frac{de_m^{nv}}{d\theta_r} = \frac{8\gamma^3 q_0(1+\theta_r)(1+\theta_m)}{t_r t_m\beta^2(9-8G_m-8G_r)^2} > 0$, $\frac{de_r^{nv}}{d\theta_r} = \frac{2q_0\gamma(9-8G_m+8G_r)}{t_r\beta(9-8G_m-8G_r)^2} > 0$, $\frac{dw^{nv}}{d\theta_m} = \frac{12\gamma^2 q_0(1+\theta_m)}{t_m\beta^2(9-8G_m-8G_r)^2} > 0$, $\frac{dw^{nv}}{d\theta_r} = \frac{12\gamma^2 q_0(1+\theta_r)}{t_r\beta^2(9-8G_m-8G_r)^2} > 0$, $\frac{dp^{nv}}{d\theta_m} = \frac{24\gamma^2 q_0(1+\theta_m)}{t_m\beta^2(9-8G_m-8G_r)^2} > 0$, $\frac{dp^{nv}}{d\theta_r} = \frac{24\gamma^2 q_0(1+\theta_r)}{t_r\beta^2(9-8G_m-8G_r)^2} > 0$, $\frac{dq^{nv}}{d\theta_m} = \frac{12q_0\gamma^2(1+\theta_m)}{\beta t_m(9-8G_m-8G_r)^2} > 0$, and $\frac{dq^{nv}}{d\theta_r} = \frac{12q_0\gamma^2(1+\theta_r)}{\beta t_r(9-8G_m-8G_r)^2} > 0$, then e_m^{nv}, e_r^{nv}, w^{nv}, p^{nv}, T_r^{nv}, T_m^{nv}, and q^{nv} all increase in θ_m and θ_r. 2) VN cooperation model: From Table 2, we obtain $\frac{dT_r^{cv}}{d\theta_m} = \frac{128q_0^2\gamma^4(1+\theta_r)^2(1+\theta_m)}{t_m t_r\beta^3(9-16G_m-16G_r)^3} > 0$, $\frac{dT_r^{cv}}{d\theta_r} = \frac{16q_0^2\gamma^2(1+\theta_r)(9-16G_m+16G_r)}{t_r\beta^3(9-16G_m-16G_r)^3} > 0$, $\frac{dT_m^{cv}}{d\theta_m} = \frac{16q_0^2\gamma^2(1+\theta_m)(9+16G_m-16G_r)}{t_m\beta^3(9-16G_m-16G_r)^3} > 0$,

$\frac{dT_m^{cv}}{d\theta_r} = \frac{128q_0^2\gamma^4(1+\theta_r)(1+\theta_m)^2}{t_m t_r \beta^3(9-16G_m-16G_r)^3} > 0$, $\frac{de_m^{cv}}{d\theta_m} = \frac{4\gamma q_0(9+16G_m-16G_r)}{t_m\beta(9-16G_m-16G_r)^2} > 0$, $\frac{de_r^{cv}}{d\theta_m} = \frac{32\gamma^3 q_0(1+\theta_r)(1+\theta_m)}{\beta^2 t_r t_m(9-16G_m-16G_r)^2} > 0$, $\frac{de_m^{cv}}{d\theta_r} = \frac{32\gamma^3 q_0(1+\theta_r)(1+\theta_m)}{\beta^2 t_r t_m(9-16G_m-16G_r)^2} > 0$, $\frac{de_r^{cv}}{d\theta_r} = \frac{4\gamma q_0(9-16G_m+16G_r)}{t_r\beta(9-16G_m-16G_r)^2} > 0$, $\frac{dw^{cv}}{d\theta_m} = \frac{24\gamma^2 q_0(1+\theta_m)}{t_m\beta^2(9-16G_m-16G_r)^2} > 0$, $\frac{dw^{cv}}{d\theta_r} = \frac{24\gamma^2 q_0(1+\theta_r)}{t_r\beta^2(9-16G_m-16G_r)^2} > 0$, $\frac{dp^{cv}}{d\theta_m} = \frac{48\gamma^2 q_0(1+\theta_m)}{t_m\beta^2(9-16G_m-16G_r)^2} > 0$, $\frac{dp^{cv}}{d\theta_r} = \frac{48\gamma^2 q_0(1+\theta_r)}{t_r\beta^2(9-16G_m-16G_r)^2} > 0$, $\frac{dq^{cv}}{d\theta_m} = \frac{24q_0\gamma^2(1+\theta_m)}{\beta t_m(9-16G_m-16G_r)^2} > 0$, and $\frac{dq^{cv}}{d\theta_r} = \frac{24q_0\gamma^2(1+\theta_r)}{\beta t_r(9-16G_m-16G_r)^2} > 0$, then e_m^{cv}, e_r^{cv}, w^{cv}, p^{cv}, T_r^{cv}, T_m^{cv}, and q^{cv} all increase in θ_m and θ_r.

(3) RS model: From Equation (GC), we obtain $2-3G_m-3G_r > 0$. 1) RS non-cooperation model: From Table 2, we obtain $\frac{dT_r^{nr}}{d\theta_m} = \frac{q_0^2\gamma^4(1+\theta_r)^2(1+\theta_m)}{8t_m t_r\beta^2(2-G_m-2G_r)^3} > 0$, $\frac{dT_r^{nr}}{d\theta_r} = \frac{q_0^2\gamma^2(1+\theta_r)(2-G_m+2G_r)}{16t_r\beta^2(2-G_m-2G_r)^3} > 0$, $\frac{dT_m^{nr}}{d\theta_m} = \frac{q_0^2\gamma^2(1+\theta_m)(2+G_m-2G_r)}{64t_m\beta^2(2-G_m-2G_r)^3} > 0$, $\frac{dT_m^{nr}}{d\theta_r} = \frac{q_0^2\gamma^4(1+\theta_r)(1+\theta_m)^2}{16t_m t_r\beta^2(2-G_m-2G_r)^3} > 0$, $\frac{de_m^{nr}}{d\theta_m} = \frac{q_0\gamma(2+G_m-2G_r)}{4t_m\beta(2-2G_m-G_r)^2} > 0$, $\frac{de_r^{nr}}{d\theta_m} = \frac{\gamma^3 q_0(1+\theta_r)(1+\theta_m)}{4t_r t_m\beta^2(2-G_m-2G_r)^2} > 0$, $\frac{de_m^{nr}}{d\theta_r} = \frac{\gamma^3 q_0(1+\theta_r)(1+\theta_m)}{4t_r t_m\beta^2(2-G_m-2G_r)^2} > 0$, $\frac{de_r^{nr}}{d\theta_r} = \frac{q_0\gamma(2-G_m+2G_r)}{2t_r\beta(2-G_m-2G_r)^2} > 0$, $\frac{dw^{nr}}{d\theta_m} = \frac{\gamma^2 q_0(1+\theta_m)}{4t_m\beta^2(2-G_m-2G_r)^2} > 0$, $\frac{dw^{nr}}{d\theta_r} = \frac{\gamma^2 q_0(1+\theta_r)}{2t_r\beta^2(2-G_m-2G_r)^2} > 0$, $\frac{dp^{nr}}{d\theta_m} = \frac{3\gamma^2 q_0(1+\theta_m)}{4t_m\beta^2(2-G_m-2G_r)^2} > 0$, $\frac{dp^{nr}}{d\theta_r} = \frac{3\gamma^2 q_0(1+\theta_r)}{2t_r\beta^2(2-G_m-2G_r)^2} > 0$, $\frac{dq^{nr}}{d\theta_m} = \frac{q_0\gamma^2(1+\theta_m)}{4\beta t_m(2-G_m-2G_r)^2} > 0$, and $\frac{dq^{nr}}{d\theta_r} = \frac{q_0\gamma^2(1+\theta_r)}{2\beta t_r(2-G_m-2G_r)^2} > 0$, then T_r^{nr}, T_m^{nr}, e_m^{nr}, e_r^{nr}, w^{nr}, p^{nr}, and q^{nr} all increase in θ_m and θ_r. 2) RS cooperation model: From Table 2, we obtain $\frac{dT_r^{cr}}{d\theta_m} = \frac{27q_0^2\gamma^4(1+\theta_r)^2(1+\theta_m)}{32t_m t_r\beta^2(2-3G_m-3G_r)^3} > 0$, $\frac{dT_r^{cr}}{d\theta_r} = \frac{9q_0^2\gamma^2(1+\theta_r)(2-3G_m+3G_r)}{16t_r\beta^2(2-3G_m-3G_r)^3} > 0$, $\frac{dT_m^{cr}}{d\theta_m} = \frac{9q_0^2\gamma^2(1+\theta_m)(2+3G_m-3G_r)}{16t_m\beta^2(2-3G_m-3G_r)^3} > 0$, $\frac{dT_m^{cr}}{d\theta_r} = \frac{27q_0^2\gamma^4(1+\theta_r)(1+\theta_m)^2}{32t_m t_r\beta^2(2-3G_m-3G_r)^3} > 0$, $\frac{de_m^{cr}}{d\theta_m} = \frac{3\gamma q_0(2+3G_m-3G_r)}{4t_m\beta(2-3G_m-3G_r)^2} > 0$, $\frac{de_r^{cr}}{d\theta_m} = \frac{9\gamma^3 q_0(1+\theta_r)(1+\theta_m)}{8\beta^2 t_r t_m(2-3G_m-3G_r)^2} > 0$, $\frac{de_m^{cr}}{d\theta_r} = \frac{9\gamma^3 q_0(1+\theta_r)(1+\theta_m)}{8\beta^2 t_r t_m(2-3G_m-3G_r)^2} > 0$, $\frac{de_r^{cr}}{d\theta_r} = \frac{3\gamma q_0(2-3G_m+3G_r)}{4t_r\beta(2-3G_m-3G_r)^2} > 0$, $\frac{dw^{cr}}{d\theta_m} = \frac{3\gamma^2 q_0(1+\theta_m)}{4t_m\beta^2(2-3G_m-3G_r)^2} > 0$, $\frac{dw^{cr}}{d\theta_r} = \frac{3\gamma^2 q_0(1+\theta_r)}{4t_r\beta^2(2-3G_m-3G_r)^2} > 0$, $\frac{dp^{cr}}{d\theta_m} = \frac{9\gamma^2 q_0(1+\theta_m)}{4t_m\beta^2(2-3G_m-3G_r)^2} > 0$, $\frac{dp^{cr}}{d\theta_r} = \frac{9\gamma^2 q_0(1+\theta_r)}{4t_r\beta^2(2-3G_m-3G_r)^2} > 0$, $\frac{dq^{cr}}{d\theta_m} = \frac{3q_0\gamma^2(1+\theta_m)}{4\beta t_m(2-3G_m-3G_r)^2} > 0$, and $\frac{dq^{cr}}{d\theta_r} = \frac{3q_0\gamma^2(1+\theta_r)}{4\beta t_r(2-3G_m-3G_r)^2} > 0$, then T_r^{cr}, T_m^{cr}, e_m^{cr}, e_r^{cr}, w^{cr}, p^{cr}, and q^{cr} all increase in θ_m and θ_r.

Proof of Proposition 5: From Equations (GC) and (GCV), we obtain $2-3G_m-3G_r > 0$ and $9-16G_m-16G_r > 0$.

(1) MS non-cooperation model: From Table 2 and Equation (2), we obtain $\frac{d\pi_r(p^{nm},e_r^{nm})}{d\theta_r} = \frac{\gamma^2 q_0^2(1+\theta_r)(2+2G_m-G_r)}{16t_r\beta^2(2-2G_m-G_r)^3} > 0$ and $\frac{d\pi_r(p^{nm},e_r^{nm})}{d\theta_m} = \frac{\gamma^2 q_0^2(2-G_r)(1+\theta_m)}{4t_m(2-2G_m-G_r)^3} > 0$, then $\pi_r(p^{nm}, e_r^{nm})$ increases in θ_r and θ_m. From Table 2 and Equation (1), we obtain $\frac{d\pi_m(w^{nm},e_m^{nm})}{d\theta_r} = \frac{\gamma^2 q_0^2(1+\theta_r)(1-G_m)}{2t_r(2-2G_m-G_r)^3} > 0$ and $\frac{d\pi_m(w^{nm},e_m^{nm})}{d\theta_m} = \frac{\gamma^2 q_0^2(1+\theta_m)(2-2G_m+G_r)}{4t_m\beta^2(2-2G_m-G_r)^3} > 0$, then $\pi_m(w^{nm}, e_m^{nm})$ increases in θ_r and θ_m. From Table 2 and Equation (4), we

obtain $\frac{d\pi_t^n(w^{nm},e_m^{nm},p^{nm},e_r^{nm})}{d\theta_r}=\frac{\gamma^2q_0^2(1+\theta_r)(10-6G_m-G_r)}{16t_r\beta^2(2-2G_m-G_r)^3}>0$ and $\frac{d\pi_t^n(w^{nm},e_m^{nm},p^{nm},e_r^{nm})}{d\theta_m}=\frac{t_r\gamma^2q_0^2(1+\theta_m)(2-G_m)}{2t_m\beta^2(2-2G_m-G_r)^3}>0$, then $\pi_t^n(w^{nm},e_m^{nm},p^{nm},e_r^{nm})$ increases in θ_r and θ_m. VN non-cooperation model: From Table 2 and Equation (2), we obtain $\frac{d\pi_r(p^{nv},e_r^{nv})}{d\theta_r}=\frac{4\gamma^2q_0^2(1+\theta_r)(9+8G_m-8G_r)}{t_r\beta^2(9-8G_m-8G_r)^3}>0$ and $\frac{d\pi_r(p^{nv},e_r^{nv})}{d\theta_m}=\frac{8\gamma^2q_0^2(9-8G_r)(1+\theta_m)}{t_m\beta^2(9-8G_m-8G_r)^3}>0$, then $\pi_r(p^{nv},e_r^{nv})$ increases in θ_r and θ_m. From Table 2 and Equation (1), we obtain $\frac{d\pi_m(w^{nv},e_m^{nv})}{d\theta_r}=\frac{8\gamma^2q_0^2(1+\theta_r)(9-8G_m)}{t_r\beta^2(9-8G_m-8G_r)^3}>0$ and $\frac{d\pi_m(w^{nv},e_m^{nv})}{d\theta_m}=\frac{4\gamma^2q_0^2(1+\theta_m)(9-8G_m+8G_r)}{t_m\beta^2(9-8G_m-8G_r)^3}>0$, then $\pi_m(w^{nv},e_m^{nv})$ increases in θ_r and θ_m. From Table 2 and Equation (4), we obtain $\frac{d\pi_t^n(w^{nv},e_m^{nv},p^{nv},e_r^{nv})}{d\theta_r}=\frac{4\gamma^2q_0^2(1+\theta_r)(27-8G_m-8G_r)}{t_r\beta^2(9-8G_m-8G_r)^3}>0$ and $\frac{d\pi_t^n(w^{nv},e_m^{nv},p^{nv},e_r^{nv})}{d\theta_m}=\frac{4\gamma^2q_0^2(1+\theta_m)(27-8G_m-8G_r)}{81t_m\beta^2(9-8G_m-8G_r)^3}>0$, then $\pi_t^n(w^{nv},e_m^{nv},p^{nv},e_r^{nv})$ increases in θ_r and θ_m. RS non-cooperation model: From Table 2 and Equation (2), we obtain $\frac{d\pi_r(p^{nr},e_r^{nr})}{d\theta_r}=\frac{\gamma^2q_0^2(1+\theta_r)(2+2G_m-G_r)}{4t_r\beta^2(2-G_m-2G_r)^3}>0$ and $\frac{d\pi_r(p^{nr},e_r^{nr})}{d\theta_m}=\frac{\gamma^2q_0^2(1-G_r)(1+\theta_m)}{2t_m(2-G_m-2G_r)^3}>0$, then $\pi_r(p^{nr},e_r^{nr})$ increases in θ_r and θ_m. From Table 2 and Equation (1), we obtain $\frac{d\pi_m(w^{nr},e_m^{nr})}{d\theta_r}=\frac{\gamma^2q_0^2(1+\theta_r)(2-G_m)}{4t_r(2-G_m-2G_r)^3}>0$ and $\frac{d\pi_m(w^{nr},e_m^{nr})}{d\theta_m}=\frac{\gamma^2q_0^2(1+\theta_m)(2-G_m+2G_r)}{16t_m\beta^2(2-G_m-2G_r)^3}>0$, then $\pi_m(w^{nr},e_m^{nr})$ increases in θ_r and θ_m. From Table 2 and Equation (4), we obtain $\frac{d\pi_t^n(w^{nr},e_m^{nr},p^{nr},e_r^{nr})}{d\theta_r}=\frac{\gamma^2q_0^2(1+\theta_r)(2-G_r)}{16t_r\beta^2(2-G_m-2G_r)^3}>0$ and $\frac{d\pi_t^n(w^{nr},e_m^{nr},p^{nr},e_r^{nr})}{d\theta_m}=\frac{t_r\gamma^2q_0^2(1+\theta_m)(10-G_m-6G_r)}{2t_m\beta^2(2-G_m-2G_r)^3}>0$, then $\pi_t^n(w^{nr},e_m^{nr},p^{nr},e_r^{nr})$ increases in θ_r and θ_m. Therefore, for the non-cooperation model, $\pi_r(p^{nj},e_r^{nj})$, $\pi_m(w^{nj},e_m^{nj})$, and $\pi_t^n(w^{nj},e_m^{nj},p^{nj},e_r^{nj})$ increase in θ_m and θ_r; where $j=m,v,r$.

(2) MS cooperation model: From Table 2 and Equation (3), we obtain $\frac{d\pi_t^c(e_m^{cm},p^{cm},e_r^{cm})}{d\theta_r}=\frac{9\gamma^2q_0^2(1+\theta_r)}{16\beta^2t_r(2-3G_m-3G_r)^2}>0$ and $\frac{d\pi_t^c(e_m^{cm},p^{cm},e_r^{cm})}{d\theta_m}=\frac{9\gamma^2q_0^2(1+\theta_m)}{16\beta^2t_m(2-3G_m-3G_r)^2}>0$, then $\pi_t^c(e_m^{cm},p^{cm},e_r^{cm})$ increases in θ_r and θ_m. From Table 2 and Equation (2), we obtain $\pi_r(p^{cm},e_r^{cm})=\frac{q_0^2(2-9G_r)}{8\beta(2-3G_m-3G_r)^2}>0$, then $2-9G_r>0$. Therefore, if $\frac{d\pi_r(p^{cm},e_r^{cm})}{d\theta_m}=\frac{\gamma^2q_0^2(2-9G_r)(1+\theta_m)}{8\beta^2t_m(2-3G_m-3G_r)^3}>0$, then $\pi_r(p^{cm},e_r^{cm})$ increases in θ_m. Similarly, from Table 2 and Equation (1), we obtain $\pi_m(w^{cm},e_m^{cm})=\frac{q_0^2(4-9G_m)}{8\beta(2-3G_m-3G_r)^2}>0$, then $4-9G_m>0$. Therefore, if $\frac{d\pi_m(w^{cm},e_m^{cm})}{d\theta_r}=\frac{3\gamma^2q_0^2(1+\theta_r)(4-9G_m)}{4\beta^2t_r(2-3G_m-3G_r)^3}>0$, then $\pi_m(w^{cm},e_m^{cm})$ increases in θ_r. VN cooperation model: From Table 2 and Equation (3), we obtain $\frac{d\pi_t^c(e_m^{cv},p^{cv},e_r^{cv})}{d\theta_r}=\frac{16\gamma^2q_0^2(1+\theta_r)}{\beta^2t_r(9-16G_m-16G_r)^2}>0$ and $\frac{d\pi_t^c(e_m^{cv},p^{cv},e_r^{cv})}{d\theta_m}=\frac{16\gamma^2q_0^2(1+\theta_m)}{\beta^2t_m(9-16G_m-16G_r)^2}>0$, then $\pi_t^c(e_m^{cv},p^{cv},e_r^{cv})$ increases in θ_r and θ_m. From Table 2 and Equation (2), we obtain $\pi_r(p^{cv},e_r^{cv})=\frac{q_0^2(9-32G_r)}{(9-16G_m-16G_r)^2\beta}>0$, then $9-32G_r>0$. Therefore, if $\frac{d\pi_r(p^{cv},e_r^{cv})}{d\theta_m}=\frac{16\gamma^2q_0^2(9-32G_r)(1+\theta_m)}{\beta^2t_m(9-16G_m-16G_r)^3}>0$, then $\pi_r(p^{cv},e_r^{cv})$ increases in θ_m. Similarly, from Table 2 and Equation (1), we

obtain $\pi_m(w^{cv}, e_m^{cv}) = \frac{q_0^2(9-32G_m)}{(9-16G_m-16G_r)^2\beta} > 0$, then $9-32G_m > 0$. Therefore, if $\frac{d\pi_m(w^{cv},e_m^{cv})}{d\theta_r} = \frac{16\gamma^2 q_0^2(1+\theta_r)(9-32G_m)}{\beta^2 t_r(9-16G_m-16G_r)^3} > 0$, then $\pi_m(w^{cv}, e_m^{cv})$ increases in θ_r. RS cooperation model: From Table 2 and Equation (3), we obtain $\frac{d\pi_t^c(e_m^{cr},p^{cr},e_r^{cr})}{d\theta_r} = \frac{9\gamma^2 q_0^2(1+\theta_r)}{16\beta^2 t_r(2-3G_m-3G_r)^2} > 0$ and $\frac{d\pi_t^c(e_m^{cr},p^{cr},e_r^{cr})}{d\theta_m} = \frac{9\gamma^2 q_0^2(1+\theta_m)}{16\beta^2 t_m(2-3G_m-3G_r)^2} > 0$, then $\pi_t^c(e_m^{cr}, p^{cr}, e_r^{cr})$ increases in θ_r and θ_m. From Table 2 and Equation (2), we obtain $\pi_r(p^{cr}, e_r^{cr}) = \frac{q_0^2(4-9G_r)}{8\beta(2-3G_m-3G_r)^2} > 0$, then $4-9G_r > 0$. Therefore, if $\frac{d\pi_r(p^{cr},e_r^{cr})}{d\theta_m} = \frac{3\gamma^2 q_0^2(4-9G_r)(1+\theta_m)}{8\beta^2 t_m(2-3G_m-3G_r)^3} > 0$, then $\pi_r(p^{cr}, e_r^{cr})$ increases in θ_m. Similarly, from Table 2 and Equation (1), we obtain $\pi_m(w^{cr}, e_m^{cr}) = \frac{q_0^2(2-9G_m)}{8\beta(2-3G_m-3G_r)^2} > 0$, then $2-9G_m > 0$. Therefore, if $\frac{d\pi_m(w^{cr},e_m^{cr})}{d\theta_r} = \frac{3\gamma^2 q_0^2(1+\theta_r)(2-9G_m)}{8\beta^2 t_r(2-3G_m-3G_r)^3} > 0$, then $\pi_m(w^{cr}, e_m^{cr})$ increases in θ_r. Therefore, for the cooperation model, $\pi_t\left(w^{cj}, e_m^{cj}, p^{cj}, e_r^{cj}\right)$ increases in θ_m and θ_r, $\pi_m\left(w^{cj}, e_m^{cj}\right)$ increases in θ_m, and $\pi_r\left(p^{cj}, e_r^{cj}\right)$ increases in θ_r; where $j = m, v, r$.

(3) a) MS cooperation model: From Table 2, Equations (1) and (2), we obtain $\frac{d\pi_r(p^{cm},e_r^{cm})}{d\theta_r} = \frac{3\gamma^2 q_0^2(1+\theta_r)(-2+9G_m-9G_r)}{16\beta^2 t_r(2-3G_m-3G_r)^3}$ and $\frac{d\pi_m(w^{cm},e_m^{cm})}{d\theta_m} = \frac{3\gamma^2 q_0^2(1+\theta_m)(2-9G_m+9G_r)}{16\beta^2 t_m(2-3G_m-3G_r)^3}$. Let $\frac{d\pi_r(p^{cm},e_r^{cm})}{d\theta_r} = \frac{d\pi_m(w^{cm},e_m^{cm})}{d\theta_m} = 0$, we obtain $G_m - G_r = \frac{2}{9}$. If $G_m - G_r > \frac{2}{9}$, then $\frac{d\pi_r(p^{cm},e_r^{cm})}{d\theta_r} > 0$ and $\frac{d\pi_m(w^{cm},e_m^{cm})}{d\theta_m} < 0$, so $\pi_m(w^{cm}, e_m^{cm})$ decreases in θ_m and $\pi_r(p^{cm}, e_r^{cm})$ increases in θ_r. If $G_m - G_r < \frac{2}{9}$, then $\frac{d\pi_r(p^{c},e_r^{c})}{d\theta_r} < 0$ and $\frac{d\pi_m(w^{cm},e_m^{cm})}{d\theta_m} > 0$, so $\pi_m(w^{cm}, e_m^{cm})$ increases in θ_m and $\pi_r(p^{cm}, e_r^{cm})$ decreases in θ_r. Therefore, only if $G_m - G_r = \frac{2}{9}$, then both $\pi_r(p^{cm}, e_r^{cm})$ and $\pi_m(w^{cm}, e_m^{cm})$ achieve their maximum profits. b) VN cooperation model: From Table 2, Equations (1) and (2), we obtain $\frac{d\pi_r(p^{cv},e_r^{cv})}{d\theta_r} = \frac{512\gamma^2 q_0^2(1+\theta_r)(G_m-G_r)}{\beta^2 t_r(9-16G_m-16G_r)^3}$ and $\frac{d\pi_m(w^{cv},e_m^{cv})}{d\theta_m} = \frac{512\gamma^2 q_0^2(1+\theta_m)(G_r-G_m)}{\beta^2 t_m(9-16G_m-16G_r)^3}$. Let $\frac{d\pi_r(p^{cv},e_r^{cv})}{d\theta_r} = \frac{d\pi_m(w^{cv},e_m^{cv})}{d\theta_m} = 0$, we obtain $G_m = G_r$. If $G_m > G_r$, then $\frac{d\pi_r(p^{cv},e_r^{cv})}{d\theta_r} > 0$ and $\frac{d\pi_m(w^{cv},e_m^{cv})}{d\theta_m} < 0$, so $\pi_r(p^{cv}, e_r^{cv})$ increases in θ_r and $\pi_m(w^{cv}, e_m^{cv})$ decreases in θ_m. If $G_m < G_r$, then $\frac{d\pi_r(p^{cv},e_r^{cv})}{d\theta_r} < 0$ and $\frac{d\pi_m(w^{cv},e_m^{cv})}{d\theta_m} > 0$, so $\pi_r(p^{cv}, e_r^{cv})$ decreases in θ_r and $\pi_m(w^{cv}, e_m^{cv})$ increases in θ_m. Therefore, only if $G_m = G_r$ then both $\pi_r(p^{cv}, e_r^{cv})$ and $\pi_m(w^{cv}, e_m^{cv})$ achieve their maximum profits. c) RS cooperation model: From Table 2, Equations (1) and (2), we obtain $\frac{d\pi_r(p^{cr},e_r^{cr})}{d\theta_r} = \frac{3\gamma^2 q_0^2(1+\theta_r)(2+9G_m-9G_r)}{16\beta^2 t_r(2-3G_m-3G_r)^3}$ and $\frac{d\pi_m(w^{cr},e_m^{cr})}{d\theta_m} = \frac{3\gamma^2 q_0^2(1+\theta_m)(-2-9G_m+9G_r)}{16\beta^2 t_m(2-3G_m-3G_r)^3}$. Let $\frac{d\pi_r(p^{cr},e_r^{cr})}{d\theta_r} = \frac{d\pi_m(w^{cr},e_m^{cr})}{d\theta_m} = 0$, we obtain $G_r - G_m = \frac{2}{9}$. If $G_r - G_m > \frac{2}{9}$, then $\frac{d\pi_r(p^{cr},e_r^{cr})}{d\theta_r} < 0$ and $\frac{d\pi_m(w^{cr},e_m^{cr})}{d\theta_m} > 0$, so $\pi_r(p^{cr}, e_r^{cr})$ decreases in θ_r and $\pi_m(w^{cr}, e_m^{cr})$ increases in θ_m. If $G_r - G_m < \frac{2}{9}$, then $\frac{d\pi_r(p^{cr},e_r^{cr})}{d\theta_r} > 0$ and $\frac{d\pi_m(w^{cr},e_m^{cr})}{d\theta_m} < 0$, so $\pi_r(p^{cr}, e_r^{cr})$ increases in θ_r

and $\pi_m(w^{cr}, e_m^{cr})$ decreases in θ_m. Therefore, only if $G_r - G_m = \frac{2}{9}$, then both $\pi_r(p^{cr}, e_r^{cr})$ and $\pi_m(w^{cr}, e_m^{cr})$ achieve their maximum profits.

Proof of Proposition 6: From Equations (GC) and (GVC), we obtain $2 - 3G_m - 3G_r > 0$ and $3 - 4G_m - 4G_r > 0$. (1) Recall $E = (e_m + e_r)q$, from Lemma 2, we can directly derive that both E^{nj} and E^{cj} increase in θ_m and θ_r. (2) From Table 2, we obtain $\frac{dCS^{nm}}{d\theta_m} = \frac{q_0^2\gamma^2(1+\theta_m)}{4t_m\beta^2(2-2G_m-G_r)^3} > 0$, $\frac{dCS^{nm}}{d\theta_r} = \frac{q_0^2\gamma^2(1+\theta_r)}{8t_r\beta^2(2-2G_m-G_r)^3} > 0$, $\frac{dCS^{cm}}{d\theta_m} = \frac{3q_0^2\gamma^2(1+\theta_m)}{8t_m\beta^2(2-3G_m-3G_r)^3} > 0$, $\frac{dCS^{cm}}{d\theta_r} = \frac{3q_0^2\gamma^2(1+\theta_r)}{8t_r\beta^2(2-3G_m-3G_r)^3} > 0$, $\frac{dCS^{nv}}{d\theta_m} = \frac{36q_0^2\gamma^2(1+\theta_m)}{t_m\beta^2(9-8G_m-8G_r)^3} > 0$, $\frac{dCS^{nv}}{d\theta_r} = \frac{36q_0^2\gamma^2(1+\theta_r)}{t_r\beta^2(9-8G_m-8G_r)^3} > 0$, $\frac{dCS^{cv}}{d\theta_m} = \frac{72q_0^2\gamma^2(1+\theta_m)}{t_m\beta^2(9-8G_m-8G_r)^3} > 0$, $\frac{dCS^{cv}}{d\theta_r} = \frac{72q_0^2\gamma^2(1+\theta_r)}{t_r\beta^2(9-8G_m-8G_r)^3} > 0$, $\frac{dCS^{nr}}{d\theta_m} = \frac{q_0^2\gamma^2(1+\theta_m)}{8t_m\beta^2(2-G_m-2G_r)^3} > 0$, $\frac{dCS^{nr}}{d\theta_r} = \frac{q_0^2\gamma^2(1+\theta_r)}{4t_r\beta^2(2-G_m-2G_r)^3} > 0$, $\frac{dCS^{cr}}{d\theta_m} = \frac{3q_0^2\gamma^2(1+\theta_m)}{8t_m\beta^2(2-3G_m-3G_r)^3} > 0$, and $\frac{dCS^{cr}}{d\theta_r} = \frac{3q_0^2\gamma^2(1+\theta_r)}{8t_r\beta^2(2-3G_m-3G_r)^3} > 0$, then both CS^{nj} and CS^{cj} increase in θ_m and θ_r. (3) Recalling $SW = CS + \pi_m(w, e_m) + \pi_r(p, e_r) + c_eE$ and Proposition 5, we can directly derive that both SW^{nj} and SW^{cj} increase in θ_m and θ_r; where $j = m, v, r$.

Proof of Lemma 3: Integrated supply chain model: From Equation (5), we obtain $\frac{d^2\pi_t^I(e_m,p,e_r)}{dp^2} = -2\beta < 0$, so $\pi_t^I(e_m, p, e_r)$ is a concave function of p. Let $\frac{d\pi_t^I(e_m,p,e_r)}{dp} = 0$, we obtain $p = \frac{\alpha+c\beta+\gamma e_m(1+\theta_m)+\gamma e_r(1+\theta_r)}{2\beta}$. Replace $p = \frac{\alpha+c\beta+\gamma e_m(1+\theta_m)+\gamma e_r(1+\theta_r)}{2\beta}$ in $\pi_t^I(e_m, p, e_r)$, we obtain $\frac{d^2\pi_t^I(e_m,p,e_r)}{de_r^2} = -t_r + \frac{\gamma^2(1+\theta_r)^2}{2\beta}$, $\frac{d^2\pi_t^I(e_m,p,e_r)}{de_m^2} = -t_m + \frac{\gamma^2(1+\theta_m)^2}{2\beta}$, and $\frac{\partial\pi_t^{I^2}(e_m,p,e_r)}{\partial e_r\partial e_m} = \frac{\partial\pi_t^{I^2}(e_m,p,e_r)}{\partial e_m\partial e_r} = \frac{\gamma^2(1+\theta_m)(1+\theta_r)}{2\beta}$, then

$$\begin{vmatrix} \frac{\partial\pi_t^{I^2}(e_m,p,e_r)}{\partial e_m^2} & \frac{\partial\pi_t^{I^2}(e_m,p,e_r)}{\partial e_r\partial e_m} \\ \frac{\partial\pi_t^{I^2}(e_m,p,e_r)}{\partial e_m\partial e_r} & \frac{\partial\pi_t^{I^2}(e_m,p,e_r)}{\partial e_r^2} \end{vmatrix} = \frac{\gamma^2t_r(1+\theta_m)^2+t_m(-2\beta t_r+\gamma^2(1+\theta_r)^2)}{2\beta}.$$

Set $-t_r + \frac{\gamma^2(1+\theta_r)^2}{2\beta} < 0$, $-t_m + \frac{\gamma^2(1+\theta_m)^2}{2\beta} < 0$ and $-\frac{\gamma^2t_r(1+\theta_m)^2+t_m(-2\beta t_r+\gamma^2(1+\theta_r)^2)}{2\beta} > 0$, we obtain $G_m + G_r < \frac{1}{2}$, where $G_m = \frac{\gamma^2(1+\theta_m)^2}{4t_m\beta}$ and $G_r = \frac{\gamma^2(1+\theta_r)^2}{4t_r\beta}$. so $\pi_t^I(e_m, p, e_r)$ is a joint concave function of e_r and e_m. Let $\frac{\partial\pi_t^I(e_m,p,e_r)}{\partial e_r} = \frac{\partial\pi_t^I(e_m,p,e_r)}{\partial e_m} = 0$, we obtain $e_m^I = \frac{\gamma q_0(1+\theta_m)}{2t_m\beta(1-2G_m-2G_r)}$ and $e_r^I = \frac{\gamma q_0(1+\theta_r)}{2t_r\beta(1-2G_m-2G_r)}$. Replace e_m^I and e_r^I in $p = \frac{\alpha+c\beta+\gamma e_m(1+\theta_m)+\gamma e_r(1+\theta_r)}{2\beta}$, we obtain $p^I = c + \frac{q_0}{2\beta(1-2G_m-2G_r)}$.

Proof of Proposition 7: From Equation (7), we obtain $\frac{d\pi_r^p(p,e_r)}{dp} = \alpha - 2p\beta + w\beta + \gamma e_m(1 + \theta_m) + \gamma e_r(1 + \theta_r)$ and $\frac{d^2\pi_r^p(p,e_r)}{dp^2} = -2\beta < 0$, so $\pi_r^p(p, e_r)$ is a concave function of p. Let $\frac{d\pi_r^p(p,e_r)}{dp} = 0$, we get $\alpha -$

$2p\beta + w\beta + \gamma e_m(1+\theta_m) + \gamma e_r(1+\theta_r) = 0$. In order to coordinate the supply chain, replace $e_m = e_m^I$, $e_r = e_r^I$ and $p = p^I$ to aforementioned equation, we get $\beta(w-c) = 0$, then $w = c$.

In a MS power structure, the manufacturer is the market leader and gain the extra profit from the supply chain coordination, then $\pi_r^p(p^I, e_r^I) - \pi_r(p^{nm}, e_r^{nm}) = \frac{\left(6-15G_r-12G_m^2G_r+6G_r^2-4G_m\left(2-5G_r+2G_r^2\right)\right)q_0^2}{8\beta(-2+2G_m+G_r)^2(-1+2G_m+2G_r)^2} - M = 0$, then we get $M^m = \frac{\left(6-15G_r-12G_m^2G_r+6G_r^2-4G_m\left(2-5G_r+2G_r^2\right)\right)q_0^2}{8\beta(-2+2G_m+G_r)^2(-1+2G_m+2G_r)^2}$. For the manufacturer, $\pi_m^p(w^I, e_m^I) - \pi_m(w^{nm}, e_m^{nm}) = M^m - \frac{((1-2G_r)^2-4G_m^2G_r-G_m(1-8G_r+3G_r^2))q_0^2}{2\beta(-2+2G_m+G_r)^2(-1+2G_m+2G_r)^2} > 0$. So, in a MS power structure, $w = c$ and $M^m = \frac{\left(6-15G_r-12G_m^2G_r+6G_r^2-4G_m\left(2-5G_r+2G_r^2\right)\right)q_0^2}{8\beta(-2+2G_m+G_r)^2(-1+2G_m+2G_r)^2}$ is a coordination and Pareto contract for the supply chain.

In a VN power structure, the retailer and the manufacturer have same supply chain power and they gain half the extra profit from the supply chain coordination, so $\pi_r^p(p^I, e_r^I) - \pi_r(p^{nv}, e_r^{nv}) = \pi_m^p(w^I, e_m^I) - \pi_m(w^{nv}, e_m^{nv})$. Since $\pi_r^p(p^I, e_r^I) - \pi_r(p^{nv}, e_r^{nv}) = \frac{5(9-16G_m^2-26G_r+16G_r^2)q_0^2}{4\beta(-1+2G_m+2G_r)^2(-9+8G_m+8G_r)^2} - M$ and $\pi_m^p(w^I, e_m^I) - \pi_m(w^{nv}, e_m^{nv}) = M - \frac{(-8G_m^2-G_m(7-64G_r)+18(1-2G_r)^2)q_0^2}{2\beta(-1+2G_m+2G_r)^2(-9+8G_m+8G_r)^2}$. So, $M^v = \frac{(81-96G_m^2-274G_r+224G_r^2+2G_m(-7+64G_r))q_0^2}{8\beta(-1+2G_m+2G_r)^2(-9+8G_m+8G_r)^2}$. In a VN power structure, $w = c$ and $M^v = \frac{(81-96G_m^2-274G_r+224G_r^2+2G_m(-7+64G_r))q_0^2}{8\beta(-1+2G_m+2G_r)^2(-9+8G_m+8G_r)^2}$ is a coordination and Pareto contract for the supply chain.

In a RS power structure, the retailer is the market leader and gain the extra profit from the supply chain coordination. So, for the manufacturer, $\pi_m^p(w^I, e_m^I) - \pi_m(w^{nr}, e_m^{nr}) = M - \frac{(2(1-2G_r)^2+G_m^2(-4+8G_r)+G_m(7-12G_r+12G_r^2))q_0^2}{8\beta(-2+G_m+2G_r)^2(-1+2G_m+2G_r)^2} = 0$, then we get $M^r = \frac{(2(1-2G_r)^2+G_m^2(-4+8G_r)+G_m(7-12G_r+12G_r^2))q_0^2}{8\beta(-2+G_m+2G_r)^2(-1+2G_m+2G_r)^2}$. For the retailer, $\pi_r^p(p^I, e_r^I) - \pi_r(w^{nr}, e_r^{nr}) = \frac{(2-6G_r+4G_r^2+G_m^2(-7+6G_r)+4G_m(1-3G_r+2G_r^2))q_0^2}{4\beta(-2+G_m+2G_r)^2(-1+2G_m+2G_r)^2} - M^r > 0$. So, in a RS power structure, $w = c$ and $M^r = \frac{(2(1-2G_r)^2+G_m^2(-4+8G_r)+G_m(7-12G_r+12G_r^2))q_0^2}{8\beta(-2+G_m+2G_r)^2(-1+2G_m+2G_r)^2}$ is a coordination and Pareto contract for the supply chain.

So, the supply chain can be coordinated with the two-part tariff contract, and the condition satisfies $w = c$ and $M^m = \frac{\left(6-15G_r-12G_m^2G_r+6G_r^2-4G_m\left(2-5G_r+2G_r^2\right)\right)q_0^2}{8\beta(-2+2G_m+G_r)^2(-1+2G_m+2G_r)^2}$ in a MS power structure, $M^v = \frac{(81-96G_m^2-274G_r+224G_r^2+2G_m(-7+64G_r))q_0^2}{8\beta(-1+2G_m+2G_r)^2(-9+8G_m+8G_r)^2}$ in a VN power structure, and $M^r = \frac{(2(1-2G_r)^2+G_m^2(-4+8G_r)+G_m(7-12G_r+12G_r^2))q_0^2}{8\beta(-2+G_m+2G_r)^2(-1+2G_m+2G_r)^2}$ in a RS power structure.

Proof of Corollary 2: From Proposition 7, we get that $M^m - M^v =$

$\frac{-((162-335G_r+287G_r^2-80G_r^3+192G_m^3(-1+2G_r)+4G_m^2(129-264G_r+160G_r^2)+G_m(-484+978G_r-880G_r^2+256G_r^3))q_0^2)}{8\beta(-2+2G_m+G_r)^2(-1+2G_m+2G_r)(-9+8G_m+8G_r)^2}$. Set $F_1(G_m) = 162 - 335G_r + 287G_r^2 - 80G_r^3 + 192G_m^3(-1+2G_r) + 4G_m^2(129 - 264G_r + 160G_r^2) + G_m(-484 + 978G_r - 880G_r^2 + 256G_r^3)$, $F_2(G_m) = \frac{dF_1(G_m)}{G_m} = -484 + 978G_r - 880G_r^2 + 256G_r^3 + 576G_m^2(-1+2G_r) + 8G_m(129 - 264G_r + 160G_r^2)$, $-1+2G_r < 0$, then $F_1(G_m)$ is a concave function. If $0.2279 < G_r < \frac{1}{2} - G_r$, there are two roots for $F_2(G_m)$, $G_{m1} = \frac{-129+264G_r-160G_r^2-\sqrt{-783+1944G_r+8880G_r^2-11904G_r^3+7168G_r^4}}{144(-1+2G_r)}$, $G_{m2} = \frac{-129+264G_r-160G_r^2+\sqrt{-783+1944G_r+8880G_r^2-11904G_r^3+7168G_r^4}}{144(-1+2G_r)} < G_{m1}$. $G_{m2} - \left(\frac{1}{2} - G_r\right) = \frac{-57-24G_r+128G_r^2+\sqrt{-783+1944G_r+8880G_r^2-11904G_r^3+7168G_r^4}}{144(-1+2G_r)} > 0$. So $F_2(G_m) < 0$ and $F_1(G_m)$ decrease in G_m. $F_1\left(G_m = \frac{1}{2} - G_r\right) = 25(1+G_r)^2 > 0$, so $M^m > M^v$. Similarly, from Proposition 8, we get that $M^v - M^r = \frac{-((162-484G_r+516G_r^2-192G_r^3+16G_m^3(-5+16G_r)+G_m^2(287-880G_r+640G_r^2)+G_m(-335+978G_r-1056G_r^2+384G_r^3))q_0^2)}{8\beta(-2+G_m+2G_r)^2(-1+2G_m+2G_r)(-9+8G_m+8G_r)^2}$ and $M^v > M^r$.