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RESEARCH ARTICLE

# Cross-ownership and strategic environmental corporate social responsibility under price competition

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**Abstract**

This paper examines the impact of cross-ownership on the strategic incentive of environmental corporate social responsibility (ECSR) within a green managerial delegation contract in a triopoly market engaged in price competition. It demonstrates that bilateral cross-ownership between insiders provides weak incentives to undertake ECSR, which has a non-monotone relationship with cross-ownership shares, while it provides strong incentives for outsiders, which increases the ECSR level as cross-ownership increases. It also compares unilateral cross-ownership and finds that a firm that owns shares in its rival has a greater incentive to undertake ECSR than its partially-owned rival, while an outsider has more incentive than firms in bilateral scenarios. These findings reveal that a firm's incentive to increase a market price through ECSR critically depends on its cross-ownership share, while it decreases environmental damage and increases social welfare when the environmental damage is serious.

**Keywords:** bilateral cross-ownership; cross-ownership; environmental corporate social responsibility; price competition; triopoly market; unilateral cross-ownership

**JEL classification:** H23; L13; M14

## 1. Introduction

Cross-ownership is common in many industries and thus has become a subject of business strategy and policy discussion in numerous economies.[1] As evidenced in real-world cases, several high-pollution industries under cross-ownership were observed. For example, Sinopec, the worst polluter among oil industries in China, holds a 40 per cent stake in Repsol YPF Brasil and 30 per cent in Petrogal Brasil. In the airline industry, Delta Air

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[1] Cross-ownership is the situation in which firms undertake passive investments in rival firms, obtaining a share in the profit but not in the decision-making. For practical examples of cross-ownership in the real world, see Liker and Choi (2004), Li *et al.* (2015), Liu *et al.* (2018), Bárcena-Ruiz and Sagasta (2021), Fanti and Buccella (2021), Cho *et al.* (2022), and Xing *et al.* (2024), among others.

Lines and China Eastern Airlines each hold 8.8 per cent stakes in the Air France KLM Group, and Iberia holds a 9.49 per cent stake in the low-cost carrier Vueling and a 0.95 per cent stake in Royal Air Maroc. In the automobile industry, a significant pollution contributor, Korean automobile producer Hyundai, owns 33.9 per cent of Kia, and Nissan holds a 34 per cent stake in Mitsubishi Motors. Additionally, Toyota acquired a 5 per cent stake in the Chinese iron and steel company BFS in 2015 to help expand the market for hybrid cars in China.

A firm may be interested in acquiring a strategic stake in its rival because it can consider the effect of its output decision on the rival's profits. This is because cross-ownership can reduce competition in product and service markets and raise prices as a collusive device (Reynolds and Snapp, 1986). However, it may lead firms to internalize industry-wide externalities such as research spillover and emissions through horizontal and vertical relations, which can improve social welfare (Bayona and López, 2018; López and Vives, 2019; Sato and Matsumura, 2020; Anton *et al*., 2021; Chen *et al*., 2023). This indicates that cross-ownership might significantly influence environmental management and business strategy, especially in high-pollution industries.

In contrast, due to public awareness of environmental and climate damage and financial pressure from institutional investors, firm owners in these industries have also adopted environmental incentives as an alternative form of performance evaluation in their managerial delegation contracts.[2] According to PwC's global investor survey 2022 and OCEG-ESG-survey 2021,[3] 52 per cent of 530 corporate executives plan to base or are already basing executive compensation on ESG (environmental, social, and governance) factors, and 45 per cent of the companies listed on the FTSE 100 have an ESG factor in their annual bonuses, long-term incentive plans (LTIPs), or both. The most common LTIP is linked to environmental issues such as decarbonization and energy transition.

In the literature focused on green managerial delegation contracts, owners establish environmental incentives while managers engage in emission reduction, known as environmental corporate social responsibility (ECSR). Several studies have examined firms' voluntary ECSR initiatives targeting abatement activities under price competition (Liu *et al*., 2015; Hirose *et al*., 2017; Lee and Park, 2019, 2021; Park and Lee, 2023*a*). Hirose *et al*. (2017) examined the simultaneous choice of ECSR under sequential price competition and revealed that only the price follower adopts ECSR, increasing market prices and firm profits. Lee and Park (2019) also examined the sequential choice of ECSR under simultaneous price competition and showed that firms adopt ECSR to mitigate competition when the products are more substitutable. Park and Lee (2023*a*) generalized the endogenous ECSR timing choice under price competition and confirmed that ECSR-induced higher costs increase firm profits. That is, there exists a cost pass-through effect under price competition.

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[2] In a managerial delegation contract, firm owners delegate strategic decisions to managers and determine the compensatory managerial incentives. Since the pioneering works of Vickers (1985), Fershtman (1985), Fershtman and Judd (1987) and Sklivas (1987), many studies have examined different types of managerial incentives, including sales (Nakamura, 2015; Fanti *et al*., 2017; Wang and Wang, 2021), revenue (Colombo, 2022; Heywood *et al*., 2022), market share (Ritz, 2008; Jansen *et al*., 2009; Heywood and Wang, 2020), rival profits (van Witteloostuijn *et al*., 2007; Pal, 2015; Xu and Matsumura, 2022), consumer surplus (Brand and Grothe, 2015; Leal *et al*., 2018; Kim *et al*., 2019; Garcia *et al*., 2024), and environmental activities (Liu *et al*., 2015; Hirose *et al*., 2017; Xing and Lee, 2023; Xu and Lee, 2023).

[3] See https://www.pwc.com/gx/en/issues/esg/global-investor-survey-2022.html and https://www.reuters.com/business/sustainable-business/most-executives-think-their-esg-programs-fall-short-survey-finds-2021-09-15. See also oceg-esg-survey.pdf and Ritz (2022).

Recent research has also incorporated emission tax policies and examined theoretical linkages between governmental regulations and firm performance in green delegation models (Poyago-Theotoky and Yong, 2019; Buccella *et al.*, 2021, 2022, 2023; Xu *et al.*, 2022; Park and Lee, 2023*b*). Notably, Poyago-Theotoky and Yong (2019) compared a standard managerial delegation contract with sales incentives to an environmental delegation contract that rewards abatement activities. They determined that firm profits are greater under the environmental incentive-based contract. Buccella *et al.* (2023) demonstrated that sales delegation might emerge as the Pareto-inefficient equilibrium under Cournot competition, while Park and Lee (2023*b*) combined the two compensation schemes and identified an optimal combination of double delegation contracts with ECSR. However, they investigated Cournot duopoly under quantity competition and thus the ECSR-induced cost pass-through effect under price competition was not fully incorporated.

Furthermore, some studies have considered strategic associations between ECSR and industrial cooperation, such as cross-ownership or common ownership, in a green delegation model (Hirose *et al.*, 2020; Bárcena-Ruiz and Sagasta, 2021; Hirose and Matsumura, 2022; Xing and Lee, 2023; Cho and Lee, 2024). For example, Hirose *et al.* (2020) and Xu and Lee (2022) examined whether ECSR was adopted by joint-profit-maximizing industrial associations under quantity and price competitions with or without government regulations, respectively, and showed that ECSR decisions are determined by the market competition modes. Hirose and Matsumura (2022) investigated the social welfare-improving effect of common ownership when the common owner promotes ECSR. Bárcena-Ruiz and Sagasta (2021) analyzed the international coordination of environmental policies when there is cross-ownership between polluting firms that adopt ECSR. Ning *et al.* (2022) compared two timings of the game with green delegation contracts under cross-ownership and examined whether the government should precommit to an emission tax or delay the tax decision. Finally, Cho and Lee (2024) considered environmental cooperation between ECSR commitment and environmental R&D under price competition and then indicated the importance of cross-ownership in a coordination game. However, the existing literature focuses mostly on duopoly competition and rarely discusses green managerial delegation in an oligopolistic competition with an asymmetric financial network of cross-ownership.

This paper seeks to elucidate the effects of cross-ownership on ECSR in a triopoly market within a green delegation contract under price competition. It considers bilateral cross-ownership where two firms form a financially networked group and finds that insiders under cross-ownership have incentives to undertake ECSR while outsiders are more motivated to undertake ECSR than insiders. Thus, cross-ownership will provide strong (weak) incentives to undertake ECSR among outsiders (insiders) since increased ECSR causes higher prices via the cost pass-through effect, which is more profitable to outsiders through increased competitive prices. This also implies that outsiders have more reason to engage in collusive pricing with rivals through ECSR, which can increase profits. Outsiders are also observed to increase their ECSR levels as insiders' cross-ownership shares increase, while insiders have non-monotone relationships between ECSR and the degree of cross-ownership. This is because an insider already has addressed its rival firm through cross-ownership and thus, collusive incentives through ECSR are lessened, especially when the cross-ownership share is sufficiently large. As a result, cross-ownership can decrease environmental damage and increase social welfare when environmental damage is severe.

Finally, this study further considers an asymmetric ownership structure under unilateral cross-ownership where only one firm holds a share of its rival firm and compares the results with those under a bilateral cross-ownership case. Nearly all the present findings reflect a bilateral cross-ownership hold, but a firm's incentive to adopt ECSR depends on the degree of ownership asymmetry between insiders. In particular, a firm that owns a share in its rival has a stronger incentive to undertake ECSR than does a partially-owned rival or an outsider. Therefore, a firm's incentive to collude through ECSR critically depends on the share of cross-ownership and the degree of product substitutability. Additionally, cross-ownership may or may not improve welfare, depending on the degree of environmental damage. These findings have important policy implications, especially since modern enterprises are reformulating green delegation contracts; thus, antitrust authorities should also develop appropriate guidelines for shares of cross-ownership to improve both environmental quality and social welfare, especially when environmental damage is severe.

The remainder of this paper is structured as follows. Section 2 introduces the basic model. A bilateral cross-ownership case is examined in section 3. It is then compared with a unilateral cross-ownership case in section 4. Finally, section 5 concludes the paper.

## 2. The basic model

A triopoly market where three firms (firms 0, 1, and 2) provide differentiated products and compete with prices is considered. Following Singh and Vives (1984), the utility function of the representative consumer is:

$$U(q_0, q_1, q_2) = a(q_0 + q_1 + q_2) - \frac{1}{2}(q_0^2 + q_1^2 + q_2^2 + 2rq_0q_1 + 2rq_1q_2 + 2rq_0q_2),$$

where $q_i$ is the output of firm $i$ $(i = 0, 1, 2)$, $Q = q_0 + q_1 + q_2$, and $r$ $(0 < r < 1)$ denotes product substitutability between product $i$ and product $j\,(i \neq j)$. Utilizing the utility maximization problem, the following inverse demand function is obtained:[4]

$$p_i = a - q_1 - r(Q - q_i),\ i = 0,\ 1,\ 2. \tag{1}$$

Next, the following demand function is obtained:

$$q_i = \frac{1}{1 + r - 2r^2}\left[(1 - r)a - (1 + r)p_i + r\left(\sum_{j=0}^{2} p_j - p_i\right)\right], \quad i = 0, 1, 2. \tag{2}$$

Firms' production processes cause pollutant emissions. Here, one output unit is assumed to result in one pollution unit when the pollutant emission of firm $i$ is given by $e_i = q_i - y_i$ under end-of-pipe technology. Thus, firm $i$ realizes the emission reduction

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[4] Specifically, the utility maximization problem with the budget constraint yields the following maximization of consumer net surplus problem: $CS(q_0, q_1, q_2) = U(q_0, q_1, q_2) - \sum_{i=0}^{2} p_i q_i$, where the product's price is exogenously given to the consumers. Using $\frac{\partial CS(q_0,q_1,q_2)}{\partial q_i} = \frac{\partial U(q_0,q_1,q_2)}{\partial q_i} - p_i = 0 (i = 0,\ 1,\ 2)$ results in the inverse demand function.

of $y_i$ by bearing the abatement cost $I_i = (\xi y_i^2/2)$ where $\xi (\xi > 0)$ measures abatement efficiency. The greater $\xi$ is, the lower the abatement efficiency. We employ $\xi = 1$ for simplicity, which does not affect the validity of the analysis. The corresponding environmental damage is assumed to be a quadratic function of total pollutants: $D = (d/2)\left(\sum_{i=0}^{2} e_i\right)^2$, where $d\,(d > 0)$ measures the seriousness of environmental damage generated by pollution.

The profit function of each firm is:

$$\pi_i = (p_i - c)q_i - \frac{y_i^2}{2}, \quad i = 0,\ 1,\ 2, \tag{3}$$

where $c$ denotes the marginal production cost and satisfies $0 < c < a$.

Therefore, social welfare is defined as the sum of profits and consumer surplus minus total environmental damage:

$$SW = \sum_{i=0}^{2} \pi_i + CS - D, \tag{4}$$

where $CS = \frac{1}{2}(q_0^2 + q_1^2 + q_2^2 + 2rq_0q_1 + 2rq_0q_2 + 2rq_1q_2)$.

We assume that two firms (firms 1 and 2) form a financially networked group of bilateral cross-ownership where both firms hold $k$ shares of the other, and $0 < k < 0.5$. Thus, the total profit of insider $i$ (i.e., firm $i$) is: $\prod_i = (1-k)\pi_i + k\pi_j \ (i \neq j,\ i, j = 1,\ 2)$. However, firm 0 is an outsider and does not hold shares of other firms. That is, its total profit is: $\prod_0 = \pi_0$.

We also assume that the firms are organized with separations between ownership and management. A green managerial delegation model is considered where the owner of firm $i$ chooses the strategic level of ECSR to maximize its total profit $\prod_i$, but the manager of firm $i$ chooses abatement level $y_i$ and price $p_i$ to maximize the following objective function (Buccella *et al*., 2021; Xing and Lee, 2023; Cho and Lee, 2024):

$$V_i = \prod\nolimits_i - h_i e_i, \quad i = 0, 1, 2, \tag{5}$$

where $h_i\ (h_i \geq 0)$ represents the strategic degree of ECSR for firm $i$ as chosen by the owner. Firm $i$ undertakes ECSR when $h_i > 0$, but it does not undertake ECSR when $h_i = 0$. Notably, the upper bound of $h_i \in [0, 1]$ is not restricted. This implies that a firm may be more concerned about environmental damage than that which is directly caused by the firm.

The timing of the game is as follows. In the first stage, owner $i$ chooses $h_i$ to maximize total profits $\prod_i$ non-cooperatively and simultaneously. In the second stage, after observing $h_i$, manager $i$ determines $p_i$ (price) and $y_i$ (abatement level) to maximize $V_i$ non-cooperatively and simultaneously.[5] The subgame perfect equilibrium is solved using backward induction.

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[5] Note that due to the separability of the end-of-pipe technology, the results with the sequential choices between $p_i$ and $y_i$ yield the same results with simultaneous choices.

## 3. Analysis

In the second stage, manager $i$ chooses the price and abatement level. Solving the first-order conditions gives the following equilibrium price and abatement level:[6]

$$p_0 = \frac{1}{2[3r+2-(r^2+4r+2)k]}\begin{pmatrix} (1+r)[r+2-2(1+r)k]h_0 + r(1+r)(h_1 \\ +h_2) + (1-r)[3r+2-2(2r+1)k]w \end{pmatrix} \tag{6}$$

$$\begin{aligned} p_j = {} & \frac{1}{2[3r+2-(r^2+4r+2)k][3r+2-2(1+r)k]} \\ & \times \begin{pmatrix} r(1+r)(1-k)[3r+2-2(1+r)k]h_0 + (3r+2)(r+2)(1+r)(1-k)h_j \\ +r(1+r)(3r+2-rk)h_l + (3r+2)(1-r)(1-k)[3r+2-2(1+r)k]w \end{pmatrix} \end{aligned} \tag{7}$$

$$y_0 = h_0 \text{ and } y_j = \frac{h_j}{1-k},\ j,l = 1,2,\ j \neq l, \tag{8}$$

where $w = a - c$. Notably, as the degree of ECSR increases, abatement activities increase in (8). Then, due to the increase of abatement costs, prices increase along with ECSR; thus, $(\partial p_0/\partial h_0) = ((1+r)[r+2-2(1+r)k]/2[3r+2-(r^2+4r+2)k]) > 0$ and $(\partial p_1/\partial h_1) = (\partial p_2/\partial h_2) = ((3r+2)(r+2)(1+r)(1-k)/2[3r+2-(r^2+4r+2)k][3r+2-2(1+r)k]) > 0$. This implies that there is a cost pass-through effect of ECSR under price competition (Hirose *et al.*, 2017; Lee and Park, 2019; Park and Lee, 2023*a*).

In the first stage, owner $i$ chooses the optimal $h_i$ to maximize its total profits $\prod_i$. Putting (6)–(8) into (3) yields $\prod_i(h_0, h_1, h_2)$. From the first-order conditions, the following reaction function is obtained, with $A_{0b}$ and $A_{1b}$ given in appendix A:

$$\begin{aligned} h_0 = R(h_1, h_2) = {} & \frac{1}{A_{0b}}(1-k)(r+1)r^2\{r(r+1)(h_1+h_2) \\ & + (1-r)[-2(2r+1)k+3r+2]w\} \end{aligned} \tag{9}$$

$$\begin{aligned} h_j = {} & R(h_0, h_l) = \tfrac{1}{A_{1b}}r(r+1)(1-k) \\ & \times \begin{pmatrix} r^2(r+1)[-2(r+1)k+3r+2][(2r+1)k^2-(3r+2)(2k-1)]h_0 + (3r+2) \\ \times(r+1)[(2r^3+7r^2+10r+4)k^2-(4r^3+8r^2+10r+4)k+3r^3+2r^2]h_l \\ +r(1-r)(3r+2)[-2(r+1)k+3r+2][(2r+1)k^2-(3r+2)(2k-1)]w \end{pmatrix} \end{aligned} \tag{10}$$

where $j, l = 1, 2,\ j \neq l$. Thus, we have the following lemma:[7]

**Lemma 1.** (i) *$h_0$ increases with $h_j$ $(j = 1, 2)$;* (ii) *$h_j$ increases with $h_0$ $(j = 1, 2)$;* (iii) *$h_j$ increases (decreases) with $h_l$ if $k$ is small (large) $(j,\ l = 1,\ 2,\ j \neq l)$.*

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[6] Note that the second-order conditions for the entire analysis are satisfied.

[7] All proofs of lemmas and propositions are given in appendix B.

Lemma 1 represents the strategic relations of ECSR choices between insiders and outsiders when they compete on pricing under bilateral cross-ownership. First, lemma 1 (i) and (ii) state that firms' ECSR choices between insiders and outsiders are always strategic complements under price competition. This also confirms the results in a duopolistic price competition (Hirose *et al.*, 2017; Lee and Park, 2019). However, lemma 1 (iii) states that the strategic relations between the insiders depend critically on the level of cross-ownership. When $k$ is small, the insiders' ECSR choices remain strategic complements, due to the weak effects of cross-ownership, and thus each firm within the same financial network of cross-ownership increases its responsive pricing as its rival's price increases. However, when $k$ is large, insiders take more care of their rival firm due to cross-ownership, and thus both firms can pursue collusive pricing without causing additional costs associated with increased abatement activities. Therefore, the strategic relations of ECSR between insiders become strategic substitutes when they share the strong effects of cross-ownership. These properties cause significant changes in the strategic decisions related to ECSR between insiders and outsiders in the following analysis.

Solving the first-order conditions gives the following optimal ECSR levels:

$$h_0^B = \frac{r^2(1-k)(1-r^2)\Phi_b w}{\vartheta_b} \tag{11}$$

$$h_1^B = h_2^B = \frac{r^2(1-k)(1-r^2)[(2r+1)k^2+(3r+2)(1-2k)]\psi_b w}{\vartheta_b}, \tag{12}$$

where $\Phi_b$, $\psi_b$, and $\vartheta_b$ are given in appendix A.

**Proposition 1.** (i) $h_i^B > 0 (i = 0,\ 1,\ 2)$; (ii) $h_0^B > h_j^B > 0\ (j = 1, 2)$.

Proposition 1 (i) states that all firms are incentivized to undertake ECSR in a triopoly market with price competition. This is because there is a cost pass-through effect between ECSR and pricing as a collusive device to increase equilibrium prices. Proposition 1 (ii) further states that an outsider has greater motivation to undertake ECSR than an insider. That is, cross-ownership will provide strong (weak) incentives to undertake ECSR for outsiders (insiders). This is because insiders already take care of their rival firms due to cross-ownership and thus collusive incentives through cross-ownership lessen collusive incentives through ECSR since abatement activities are costly (see lemma 1 (iii)). In response, the outsider has more incentive to engage in strategic collusion with its rivals through ECSR, as ECSR choices are always strategic complements to the outsider, which increases equilibrium prices and thus profits.

By submitting (11) and (12) into (6)–(8) and (2), we obtain equilibrium prices, abatement levels and outputs: $p_i(h_0^B,\ h_1^B,\ h_2^B)$, $y_i^B = y_i(h_i^B)$, and $q_i^B = q_i(h_0^B,\ h_1^B,\ h_2^B)$, $(i = 0,\ 1,\ 2)$. Then, we identify the resulting environmental damage and social welfare in equilibrium as functions of parameters $r$, $k$ and $d$:[8]

$$D^B = \frac{d}{2}\left[\sum_{i=0}^{2}(q_i^B - y_i^B)\right]^2 \tag{13}$$

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[8] Note that to ensure $SW^B \geq 0$, $d$ cannot be too high and satisfy $0 < d \leq (G_b/Z_b^2)$ where $G_b$ and $Z_b$ are given in appendix A.

$$SW^B = \sum_{i=0}^{2} \left\{ \left[ w - (1-r)q_i^B - r\sum_{j=0}^{2} q_j^B \right] q_i^B - \frac{(y_i^B)^2}{2} \right\} + \frac{1}{2}\left[ \sum_{j=0}^{2} (q_j^B)^2 + 2r(q_0^B q_1^B + q_0^B q_2^B + q_1^B q_2^B) \right] - \frac{d}{2}\left[ \sum_{i=0}^{2} (q_i^B - y_i^B) \right]^2. \quad (14)$$

**Proposition 2.** *(i)* $(\partial h_0^B/\partial k) > 0$*; (ii) There exists* $\bar{k}(r)$*, resulting in* $(\partial h_j^B/\partial k) > (<)0$ $(j = 1, 2)$ *if* $0 < k < \bar{k}(r)(\bar{k}(r) < k < 0.5)$.

Proposition 2 implies that the outsider increases its ECSR level as the share of insider cross-ownership increases, while insiders have non-monotone relationships between the ECSR level and the share of cross-ownership. First, proposition 2 (i) states that an outsider increases its ECSR level as the share of cross-ownership by insiders grows. That is, as insiders take more care of their rival firm through cross-ownership, the strategic collusive incentive through ECSR by an outsider increases. The causes will be explained by examining insider responses. Second, proposition 2 (ii) states that insiders increase (decrease) the ECSR level as the share of cross-ownership increases if $k$ is small (large). This adverse outcome of ECSR comes from the findings in lemma 1 (iii) that an insider has already taken care of its rival firm due to cross-ownership; thus, collusive incentives through ECSR are lessened when the share of cross-ownership is sufficiently large. If $k$ is small, the cross-ownership effect is weak, which increases the incentive for ECSR to form a strategic collusion with its rivals. In that case, firms' ECSR choices between insiders and outsider are strategic complements and thus, a larger share of cross-ownership increases the outsider's ECSR as well. However, if $k$ is large, an insider's incentive to engage in strategic collusion with its rivals through cross-ownership is already strong, which decreases ECSR. In this case, an increase of $k$ has two effects on $h_0$.[9] A direct effect on $h_0$ is always positive and moves the reaction function of $h_0$ upward, while an indirect effect through changing $h_1$ and $h_2$ depends on the relative share of cross-ownership. If $k$ is relatively small, an indirect effect is always positive due to the strategic complement effect between $h_0$ and $h_j$ $(j = 1, 2)$, which moves the reaction function of $h_j$ upward, and thus $k$ increases $h_0$. However, if $k$ is relatively large, the indirect effect is negative due to the strategic substitute effect between $h_0$ and $h_j$ $(j = 1, 2)$, which moves the reaction function of $h_j$ downward. In this case, a direct effect always outweighs an indirect effect, irrespective of $k$; thus $k$ always increases $h_0$. Therefore, as $k$ increases, the strategic collusive incentives associated with ECSR by an outsider always increase, regardless of the responses of cross-ownership insiders. Notably, product substitutability also affects the effects of cross-ownership on the strategic level of ECSR, especially when the share of cross-ownership is small. Figure 1 shows that if $k$ is not high, as the degree of product substitutability increases, market competition becomes more intense; thus $k$ increases insider ECSR levels.

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[9] Using the reaction functions in (9) and (10), we obtain $h_0 = R(h_1, h_2) = f_0(r,k)(h_1 + h_2) + g_0(r,k)$ and $h_1 + h_2 = R(h_0) = f_{12}(r,k)h_0 + g_{12}(r,k)$ at the symmeric equilibrium. Then, we can prove: (i) $f_0 > 0$; $g_0 > 0$; $\frac{\partial f_0}{\partial k} > 0$; and $\frac{\partial g_0}{\partial k} > 0$; (ii) $f_{12} > 0$; $g_{12} > 0$. Additionally, there exists $\overset{\leftrightarrow}{k}(r)(0 < \overset{\leftrightarrow}{k}(r) < 0.5)$ making $\frac{\partial f_{12}}{\partial k} > (<)0$ and $\frac{\partial g_{12}}{\partial k} > (<)0$ if $k < (>)\overset{\leftrightarrow}{k}(r)$.

**Lemma 2.** (i) $(\partial p_0^B/\partial k) > 0$ *and* $(\partial p_1^B/\partial k) = (\partial p_2^B/\partial k) > 0$; (ii) $(\partial Q^B/\partial k) < 0$ *where* $Q^B = \sum_{i=0}^{2} q_i^B$; (iii) $(\partial y_0^B/\partial k) > 0$ *and* $(\partial y_1^B/\partial k) = (\partial y_2^B/\partial k) > (<)0$ *if* $k$ *is small (large) where* $Y^B = \sum_{i=0}^{2} y_i^B$; *and* (iv) $(\partial (E^B)/\partial k) < 0$ *where* $E^B = \sum_{i=0}^{2} e_i^B$.

Lemma 2 represents the effects of cross-ownership on equilibrium outcomes. First, lemma 2 (i) states that cross-ownership always increases equilibrium prices. There are two effects of the change of cross-ownership: a direct collusive effect between the insiders involved in cross-ownership and an indirect cost pass-through effect between ECSR and price. For an outsider, according to proposition 2 (i) and lemma 1, both effects are positive and therefore the outsider has a strong incentive to increase its price. However, for insiders, a direct collusive effect is positive but an indirect effect depends on the cross-ownership share (proposition 2 (ii)). Thus, it reveals that a direct effect always outweighs an indirect effect, irrespective of $k$. As a result, increased market prices decrease total industry outputs and also provide lemma 2 (ii). Furthermore, an outsider always enhances its abatement activities as it always increases its ECSR (proposition 2 (i)), but the insider increases ECSR only when the share of cross-ownership is small. This results in lemma 2 (iii). Finally, lemma 2 (iv) reveals that the decrease in total industry outputs is sufficient to reduce total industry emissions, irrespective of cross-ownership share. These results result in proposition 3.

**Proposition 3.** (i) $(\partial D^B/\partial k) < 0$; (ii) *There exists* $\bar{d}(r,k)$ $(\bar{d}(r,k) > 0)$, *resulting in* $(\partial SW^B/\partial k) < (>)0$ *if* $d < (>)\bar{d}(r,k)$.

Proposition 3 (i) states that cross-ownership can decrease environmental damage and improve environmental quality. This is a direct result of lemma 2 (iv). Proposition 3 (ii) shows that cross-ownership decreases social welfare only when environmental damage is minimal; however, it increases social welfare when environmental damage is severe. This is because a trade-off exists between the price-increasing effect (lemma 2 (i)), which decreases consumer surplus, and the environmental quality-improving effect (lemma 2 (iv)). Therefore, the latter effect outweighs the former effect only when environmental damage is significant. Figure 2 shows that more serious levels of environmental damage or higher degrees of product substitutability are required to improve social welfare when the cross-ownership share is sufficiently large. Therefore, cross-ownership may or may not improve social welfare, depending on the level of environmental damage. These findings have important policy implications because they indicate that as modern enterprises reformulate green delegation contracts, antitrust authorities should also develop guidelines for appropriate shares of cross-ownership to improve both environmental quality and social welfare, especially when environmental damage is severe.

## 4. Comparisons with unilateral cross-shareholding

In this section, an asymmetric cross-ownership structure between private firms is considered and compared with the previous findings under symmetric bilateral cross-shareholding. Specifically, a unilateral cross-shareholding case is examined where only firm 1 holds $k$ $(0 < k < 0.5)$ shares of firm 2, while the reverse is not true. The objective functions of owners are: $\prod_0 = \pi_0$, $\prod_1 = \pi_1 + k\pi_2$ and $\prod_2 = (1-k)\pi_2$. Other assumptions are the same as for the basic model.

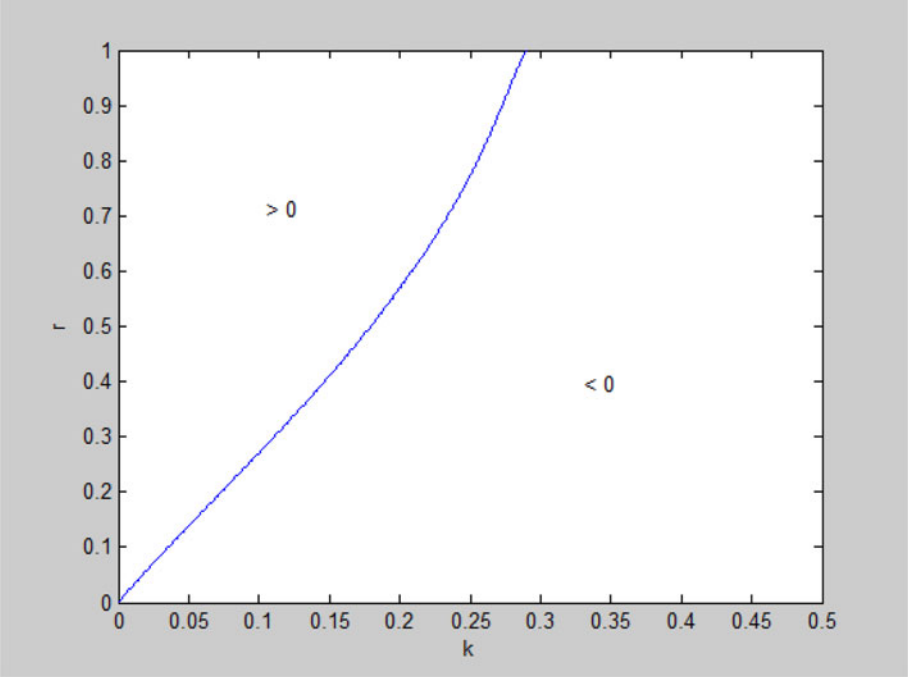

**Figure 1.** The sign of $(\partial h_j^B/\partial k)$ $(j = 1, 2)$ under bilateral cross shareholding.

Using a similar procedure, optimal ECSR levels can be obtained as follows:[10]

$$h_0^U = \frac{r^2(1-r^2)(kr+4+6r)\Phi_u w}{\vartheta_u} \tag{15}$$

$$h_1^U = \frac{r^2(1-r^2)\psi_u w}{\vartheta_u} \tag{16}$$

$$h_2^U = \frac{r^2(k+2)(1-k)(1-r^2)\rho_u w}{\vartheta_u} \tag{17}$$

where $\Phi_u$, $\psi_u$, $\rho_u$, and $\vartheta_u$ are given in appendix A. Note that ECSR choices are strategic complements for all firms in most cases, while $h_1$ decreases with $h_2$ if $k$ is large. Furthermore, comparing equilibrium results, similar results are observed in propositions 1 and 2 under bilateral cross-ownership.

**Proposition 4.** (i) $h_i^U > 0 (i = 0, 1, 2)$; (ii) $h_2^U < h_0^U < h_1^U$; (iii) $h_1^U - h_0^U < h_0^U - h_2^U$.

**Proposition 5.** (i) $(\partial h_0^U/\partial k) > 0$; (ii) $(\partial h_1^U/\partial k) > 0$; (iii) $(\partial h_2^U/\partial k) < 0$.

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[10] The detailed analysis and main findings under unilateral cross ownership are provided in the online appendix.

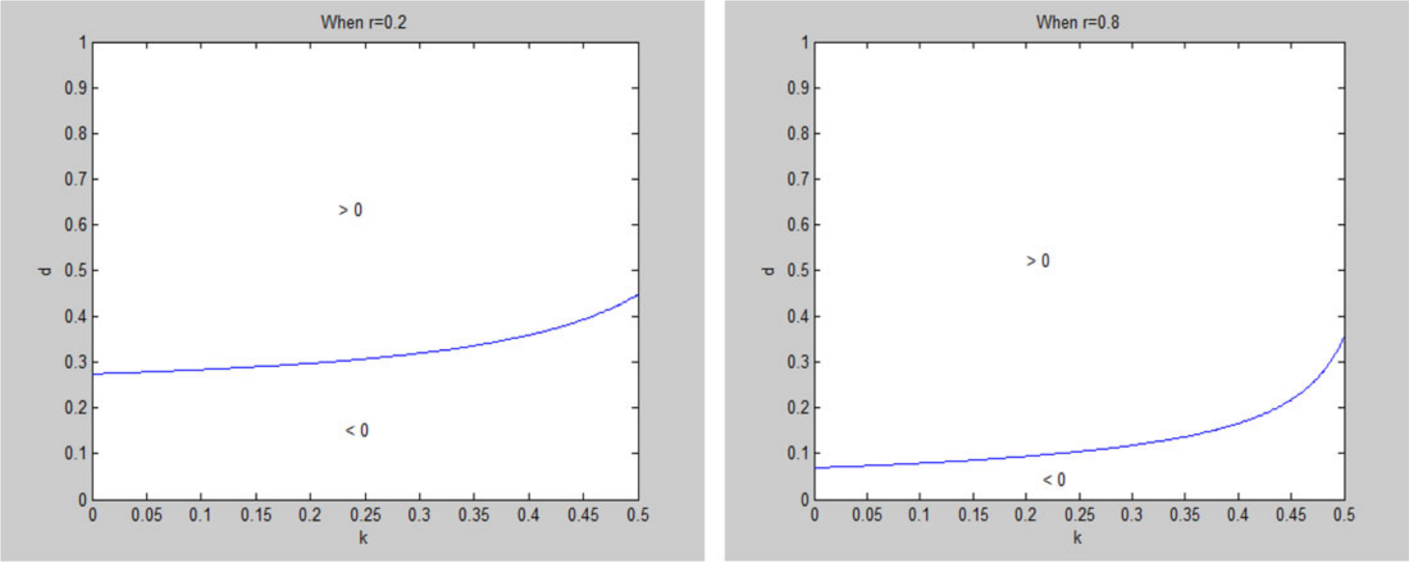

**Figure 2.** The sign of $(\partial SW^B/\partial k)$ under bilateral cross-shareholding.

As shown in proposition 4 (i), all firms are incentivized to undertake ECSR under price competition, that is, there still exists a cost pass-through effect between ECSR and price. However, due to the asymmetry of cross-ownership under unilateral cross-shareholding, firm 1 (which owns a share of firm 2), has the most incentive to undertake ECSR under collusive motivation, while firm 2 has the least incentive to undertake ECSR. This is because firm 1 (firm 2) holds larger (smaller) shares of the collusion-induced profits in the networked group and thus, adverse profit returns yield the opposite result in which firm 1 (firm 2) has more (less) motivation to engage in collusion through ECSR. Proposition 4 (ii) and (iii) further reveal that under unilateral cross-shareholding, firm 2's decreased level of ECSR is larger than firm 1's increased level. This difference induces a lower ECSR for the outsider and thus firm 0's ECSR is intermediate. Additionally, as shown in proposition 5 (i), an outsider's ECSR increases with the share of unilateral cross-ownership. However, although firm 1's ECSR level increases with the share of unilateral cross-ownership, firm 2's ECSR level decreases, contrasting with the bilateral cross-shareholding case. This is because adverse profit returns also increase as the share of cross-ownership grows. Notably, most of these findings in lemma 2 and proposition 3 under the bilateral cross-ownership hold with some modifications (see the online appendix).

Next, unilateral cross-ownership and bilateral cross-ownership are compared.

**Proposition 6.** (i) $h_0^B > h_0^U$; (ii) $h_1^B < h_1^U$; (iii) *When* $k$ *is small,* $h_2^B > h_2^U$; *When* $k$ *is large,* $h_2^B > (<) h_2^U$ *if* $k < (>) \tilde{k}(r)$.[11]

Proposition 6 (i) states that an outsider has more incentive to undertake ECSR under bilateral cross-ownership. This is because the insiders' ECSR choices are reversed under the asymmetry of cross-ownership. That is, as shown in proposition 4 (ii), under unilateral cross-ownership, firm 1 (firm 2) has more (less) incentive to undertake ECSR than the outsider firm 0; thus, unilateral cross-ownership reduces the outsider's ECSR. In particular, as shown in proposition 4 (ii) and (iii), firm 2's decreased level of ECSR is larger than firm 1's increased level, which induces a lower ECSR for firm 0 under unilateral cross-ownership. Additionally, proposition 6 (iii) states that firm 2's incentive to adopt ECSR depends on the share of cross-ownership and the degree of product substitutability. Figure 3 shows that firm 2 has more incentive under bilateral cross-ownership when firm 1 owns a small share of the profits, while the reverse is true under less severe price competition when firm 1 owns a large share of the profits.

**Proposition 7.** (i) $D^B < D^U$; (ii) *There exists* $\breve{d}(r,k)(\breve{d}(r,k) > 0)$ *making that* $SW^B > (<) SW^U$ *if* $d > (<) \breve{d}(r,k)$.

Proposition 7 (i) states that, compared with the unilateral cross-ownership case, bilateral cross-ownership can increase environmental quality. That is, the impacts of ECSR on emissions under symmetric cross-ownership are stronger; thus, total emissions under bilateral cross-ownership are more reduced. This also implies that the greater the financial networking through cross-ownership, the better the resulting environmental quality.

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[11] We find that $\tilde{k}(r)$ satisfies $0 < \tilde{k}(r) < 0.5$ and $(h_2^B - h_2^U)|_{k=\tilde{k}(r)} = 0$.

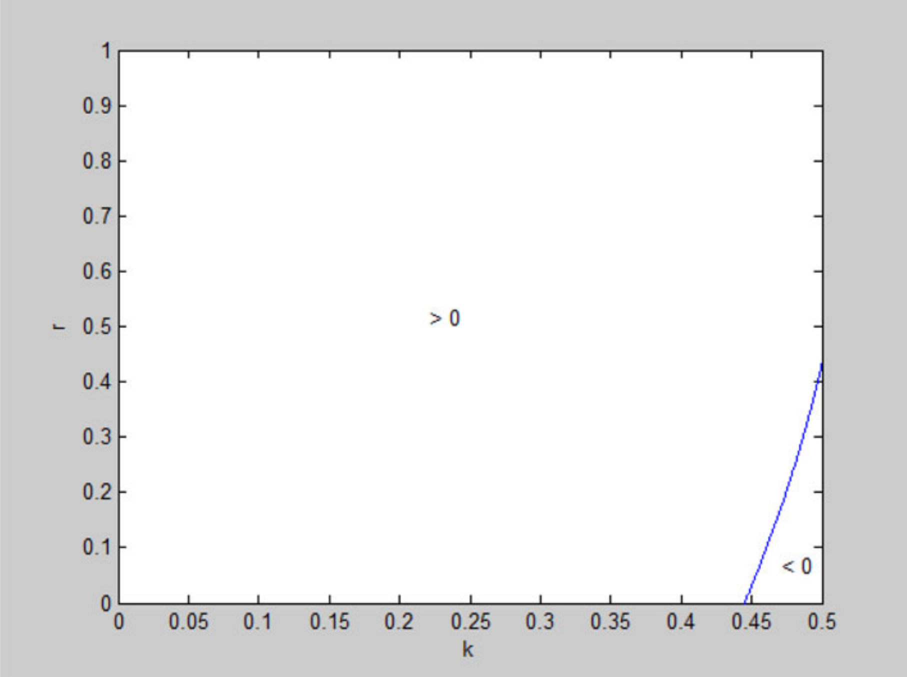

**Figure 3.** The sign of $h_2^B - h_2^U$.

This can be explained by the finding that industry-wide ECSR is lessened under unilateral cross-ownership, as shown in proposition 6 (i), $h_0^B > h_0^U$, and proposition 4 (iii), $h_1^U - h_0^U < h_0^U - h_2^U$. That is, firm 0 decreases ECSR level and firm 2's decreased ECSR level is larger than firm 1's increased ECSR level under unilateral cross-ownership. However, proposition 7 (ii) reveals that the welfare comparisons depend on the share of cross-ownership and the level of environmental damage. Figure 4 shows that social welfare is improved under bilateral cross-ownership when environmental damage is severe because cross-ownership improves environmental quality. Otherwise, the result can be reversed, since there is a trade-off between the price-increasing effect of stronger ECSR and the environmental quality-improving effect.

## 5. Concluding remarks

This paper examined the impact of cross-ownership on profitable ECSR incentives within a green delegation contract in a triopoly market. It revealed that the ECSR-induced cost pass-through effect under price competition in which the share of cross-ownership affects different incentives of financially networked firms to engage in collusive pricing through ECSR. It also demonstrated that bilateral cross-ownership provides strong incentives to undertake ECSR for outsiders but weak incentives for insiders in a financial cross-ownership network. Additionally, an outsider increases the ECSR level as the share of cross-ownership increases, while the insiders' ECSR has a non-monotone relationship. Further comparison with unilateral cross-ownership revealed that a firm

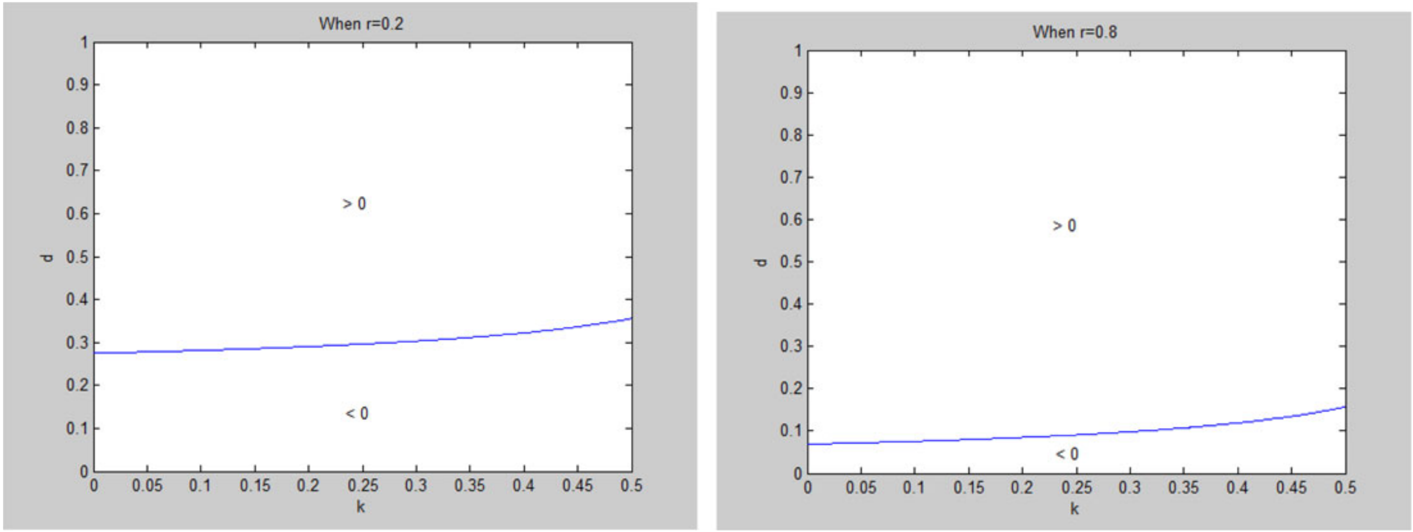

**Figure 4.** The sign of $SW^B - SW^U$.

that owns a share of its rival is more incentivized to undertake ECSR than its partially-owned rival under unilateral cross-ownership, while an outsider is more incentivized under bilateral cross-ownership. Furthermore, a firm's incentive to increase a market price through ECSR was revealed to critically depend on the share of cross-ownership and the degree of product substitutability. This could decrease environmental damage; thus increasing social welfare when the environmental damage is significant. Therefore, cross-ownership may or may not improve social welfare, depending on the severity of environmental damage. These findings have important policy implications as modern enterprises are reformulating green delegation contracts. Additionally, antitrust authorities should develop guidelines for appropriate shares of cross-ownership to improve environmental quality and social welfare, especially when environmental damage is severe.

Regarding future research, the robustness of these results must be confirmed using more general demand functions under oligopolistic competition. It is also important to examine strategic decisions through financial analysis in which the optimal share of cross-ownership is endogenously determined in association with green managerial delegation contracts and ECSR.

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**Competing interest.** The authors declare none.

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## Appendix A

$$\begin{aligned} A_{0b} = [&-2(2r+1)(r^5+7r^4+10r^3-10r^2-18r-6)k^2 \\ &+(26r^5+96r^4+10r^3-136r^2-108r-24)\,k \\ &-(r^5+37r^4+21r^3-47r^2-48r-12)], \end{aligned}$$

$$A_{1b} = \left( \begin{array}{l} -(16r^8+148r^7+460r^6+460r^5-316r^4-1056r^3 \\ \quad -896r^2-336r-48)k^4+(48r^8+526r^7 \\ \quad +1821r^6+1944r^5-1167r^4-4200r^3-3584r^2-1344r-192)k^3 \\ \quad -(36r^8+609r^7+2631r^6 \\ \quad +3189r^5-1369r^4-6124r^3-5348r^2-2016r-288)k^2+(234r^7 \\ \quad +1617r^6+2348r^5-539r^4 \\ \quad -3892r^3-3532r^2-1344r-192)k-(9r^7+345r^6+637r^5-23r^4 \\ \quad -912r^3-872r^2-336r-48) \end{array} \right),$$

$$\Phi_b = \left( \begin{array}{l} 4(2r+1)(r+1)(4r^2-3r-3)(r^2+4r+2)k^3 \\ \quad -(72r^6+430r^5+376r^4-438r^3-808r^2-416r-72)k^2 \\ \quad +(3r+2)(12r^5+119r^4+52r^3-155r^2-148r-36)k \\ \quad -(3r+2)(35r^4+20r^3-47r^2-48r-12) \end{array} \right),$$

$$\psi_b = [2(2r+1)(3r^4+10r^3-4r^2-15r-6)k-35r^4-20r^3+47r^2+48r+12],$$

$$\vartheta_b = \left(\begin{array}{l} 4(2r+1)(r+1)(r^2+4r+2)(4r^2-3r-3)(r^5+7r^4 \\ \quad +10r^3-10r^2-18r-6)k^4 \\ \quad -(48r^{11}+868r^{10}+4658r^9+7996r^8-4922r^7-27578r^6 \\ \quad -22428r^5+9426r^4+25892r^3 \\ \quad +16992r^2+5016r+576)k^3+(500r^{10}+4762r^9 \\ \quad +12112r^8-696r^7-34250r^6-35020r^5 \\ \quad +6786r^4+33298r^3+23676r^2+7296r+864)k^2 \\ \quad -(3r+2)[(12r^9+553r^8+2089r^7-316r^6 \\ \quad -5764r^5-3977r^4+2779r^3+4452r^2+1932r+288)k \\ \quad -(35r^4+20r^3-47r^2-48r-12) \\ \quad (r^4+13r^3-r^2-15r-6)] \end{array}\right),$$

$$\beta_{0b} = \left(\begin{array}{l} [(4r^4+12r^3-8r^2-18r-6)k+6+15r+2r^2 \\ \quad -11r^3][(8r+4)(r+1)(r^2+4r+2)(4r^2 \\ \quad -3r-3)k^3+(-376r^4+808r^2+416r-72r^6+438r^3 \\ \quad +72-430r^5)k^2+(3r+2)(12r^5 \\ \quad +119r^4+52r^3-155r^2-148r-36)k \\ \quad -(3r+2)(35r^4+20r^3-47r^2-48r-12)] \end{array}\right),$$

$$\beta_{1b} = \left(\begin{array}{l} (1-k)[(4r+2)(3r^4+10r^3-4r^2-15r-6)k \\ \quad -35r^4-20r^3+47r^2+48r+12][(-2r-2)(r^2+4r+2)(4r^2 \\ \quad -3r-3)k^2+(3r+2)(4r^4+21r^3-4r^2-29r-12)k \\ \quad -(3r+2)(11r^3-2r^2-15r-6)] \end{array}\right),$$

$$\lambda_b = \left(\begin{array}{l} (8r+8)(4r^2-3r-3)(r^2+4r+2)(4r^4+14r^3-4r^2 \\ \quad -21r-9)(2r+1)^2k^4-(8r+4)(132r^{10}+1471r^9 \\ \quad +4429r^8+938r^7-11987r^6-14832r^5+748r^4+13117r^3 \\ \quad +10386r^2+3438r+432)k^3+(176390r^3 \\ \quad -219976r^6+2592-93210r^7+432r^{11}+10316r^{10}+50328r^8 \\ \quad +118968r^4+50188r^9+24912r+95724r^2 \\ \quad -100696r^5)k^2-(3r+2)(888r^9+7651r^8+7339r^7-16810r^6 \\ \quad -30466r^5-4973r^4+21635r^3+19428r^2 \\ \quad +6732r+864)k+(9r+6)(r+1)(13r^3-15r-6)(35r^4 \\ \quad +20r^3-47r^2-48r-12) \end{array}\right),$$

$$\alpha_{0b} = (1-k)\left(\begin{aligned} &(8r+4)(r+1)(r^2+4r+2)(4r^2-3r-3)k^3+(-376r^4\\ &\quad +808r^2+416r-72r^6+438r^3+72-430r^5)k^2\\ &\quad +(3r+2)(12r^5+119r^4+52r^3-155r^2\\ &\quad -148r-36)k-(3r+2)(35r^4+20r^3-47r^2-48r-12)\end{aligned}\right),$$

$$\begin{aligned}\alpha_{1b} = {} & [(4r+2)(3r^4+10r^3-4r^2-15r-6)k-35r^4-20r^3+47r^2\\ & + 48r+12][(2r+1)k^2+(-6r-4)k+3r+2],\end{aligned}$$

$$\varsigma_b = \left(\begin{aligned} &(8r+8)(4r^2-3r-3)(r^2+4r+2)(3r^4+14r^3-3r^2\\ &\quad -21r-9)(2r+1)^2k^4-(8r+4)(56r^{10}+1076r^9+4205r^8\\ &\quad +1772r^7-10961r^6-14913r^5+82r^4+12759r^3+10326r^2\\ &\quad +3438r+432)k^3+(42654r^9+2592-112182r^5-211988r^6\\ &\quad +3416r^{10}-576r^{11}+107256r^4+24912r+172254r^3\\ &\quad +95196r^2+61480r^8-69046r^7)k^2+(3r+2)(144r^{10}\\ &\quad +728r^9-6383r^8-10739r^7+12362r^6+30778r^5\\ &\quad +7769r^4-20163r^3-19188r^2-6732r-864)k\\ &\quad -(9r+6)(r+1)(4r^2-3r-3)(35r^4\\ &\quad +20r^3-47r^2-48r-12)(r^2-3r-2)\end{aligned}\right),$$

$$Z_b = \left(\begin{aligned} &8(r+1)(2r+1)^2(r^2+4r+2)(4r^2-3r-3)(3r^4\\ &\quad +14r^3-3r^2-21r-9)k^4-4(2r+1)(56r^{10}+1076r^9\\ &\quad +4205r^8+1772r^7-10961r^6-14913r^5+82r^4+12759r^3\\ &\quad +10326r^2+3438r+432)k^3+(24912r\\ &\quad +107256r^4+3416r^{10}-69046r^7+42654r^9\\ &\quad +95196r^2-211988r^6+61480r^8+2592+172254r^3\\ &\quad -576r^{11}-112182r^5)k^2+(3r+2)[(144r^{10}+728r^9\\ &\quad -6383r^8-10739r^7+12362r^6+30778r^5+7769r^4\\ &\quad -20163r^3-19188r^2-6732r-864)k\\ &\quad -3(r+1)(4r^2-3r-3)(r^2-3r-2)(35r^4+20r^3-47r^2-48r-12)]\end{aligned}\right),$$

$$G_b = (2r+1)\left(\begin{array}{l}
-32(r+1)^2(2r+1)^3(r^2+4r+2)^2(4r^2-3r-3)^2(5r^9-7r^8 \\
\quad -240r^7-466r^6+578r^5+1490r^4+201r^3-1119r^2 \\
\quad -792r-162)k^8+32(r+1)(2r+1)^2(r^2+4r+2)(4r^2-3r \\
\quad -3)(240r^{15}+1744r^{14}-6758r^{13}-81214r^{12}-173251r^{11} \\
\quad +129878r^{10}+790848r^9+586263r^8-780191r^7-1459520r^6 \\
\quad -520784r^5+594909r^4+740028r^3+352548r^2 \\
\quad +82188r+7776)k^7-8(2r+1)(16128r^{21}+274240r^{20} \\
\quad +1020624r^{19}-5501796r^{18}-50093010r^{17}-113402684r^{16} \\
\quad +51424378r^{15}+601002264r^{14}+750530633r^{13}-504119609r^{12} \\
\quad -2065106995r^{11}-1489174341r^{10}+1027522973r^9 \\
\quad +2488948621r^8+1494335661r^7-270505747r^6-1011610848r^5 \\
\quad -751354860r^4-307797048r^3-75892680r^2 \\
\quad -10622016r-653184)k^6+8(27648r^{22}+740928r^{21}+5203552r^{20} \\
\quad -563676r^{19}-136132646r^{18}-499086362r^{17} \\
\quad -304785428r^{16}+1815531781r^{15}+4002092862r^{14}+764324384r^{13} \\
\quad -7366871736r^{12}-9778949650r^{11}-749056290r^{10} \\
\quad +9814393406r^9+10266080684r^8+2630593761r^7-3579135958r^6 \\
\quad -4417222140r^5-2510698512r^4-868511520r^3 \\
\quad -187636176r^2-23470560r-1306368)k^5-2(31104r^{22} \\
\quad +1791360r^{21}+21008952r^{20}+51263636r^{19}-354951580r^{18} \\
\quad -2065866769r^{17}-2455181381r^{16}+5863178696r^{15} \\
\quad +18150476174r^{14}+8694879726r^{13}-27815151602r^{12} \\
\quad -45999100572r^{11}-11195963304r^{10}+38971494395r^9 \\
\quad +47425004543r^8+15830953016r^7-13542015522r^6 \\
\quad -19332226608r^5-11524319784r^4-4105143072r^3 \\
\quad -906671232r^2-115499520r-6531840)k^4+4(3r+2)(70848r^{20} \\
\quad +1646136r^{19}+7985374r^{18}-19013012r^{17}-193611731r^{16} \\
\quad -260052490r^{15}+577983491r^{14}+1702159766r^{13} \\
\quad +475846390r^{12}-2918208952r^{11}-3659625248r^{10} \\
\quad +195127436r^9+3844050453r^8+3198629194r^7+228007967r^6 \\
\quad -1458647262r^5-1274624904r^4-560251152r^3 \\
\quad -144176976r^2-20785248r-1306368)k^3-(3r+2)(10368r^{20} \\
\quad +1368864r^{19}+14640376r^{18}+7402961r^{17}-274460046r^{16} \\
\quad -608824921r^{15}+593911918r^{14}+3008178018r^{13} \\
\quad +1746262420r^{12}-4390284866r^{11}-7020780764r^{10}-871208475r^9 \\
\quad +6343418986r^8+6122067675r^7+956195126r^6 \\
\quad -2397592296r^5-2300870928r^4-1052524944r^3-278034336r^2 \\
\quad -40891392r-2612736)k^2+2(3r+2)^2(35r^4+20r^3 \\
\quad -47r^2-48r-12)(288r^{14}+12064r^{13}+30795r^{12}-245306r^{11} \\
\quad -470232r^{10}+601968r^9+1700810r^8+203828r^7 \\
\quad -2042652r^6-1646712r^5+268323r^4+1018326r^3+595548r^2 \\
\quad +154008r+15552)k-3(r+1)(r^2-3r-2)(3r \\
\quad +2)^2(35r^4+20r^3-47r^2-48r-12)^2(8r^6+137r^5-92r^4 \\
\quad -276r^3+30r^2+171r+54)
\end{array}\right),$$

$$\begin{aligned}\Phi_u = {} & [r^2(r-1)(2+3r)(2r+1)k - 35r^4 - 20r^3 + 47r^2 \\ & + 48r + 12][r^2(6r^3 - 7r - 3)k - 35r^4 - 20r^3 + 47r^2 + 48r + 12],\end{aligned}$$

$$\psi_u = \left(\begin{array}{l} [r^2(2r+1)(9r^3+r^2-12r-6)k - (2+3r)(35r^4 \\ \quad + 20r^3 - 47r^2 - 48r - 12)][r(10r^4 - 4r^3 - 15r^2 \\ \quad - 9r - 2)k^2 + (12r^5 - 61r^4 - 42r^3 + 59r^2 + 56r + 12)k \\ \quad - 70r^4 - 40r^3 + 94r^2 + 96r + 24] \end{array}\right),$$

$$\rho_u = \left(\begin{array}{l} [r^2(r-1)(2+3r)(2r+1)k + 12 - 35r^4 - 20r^3 + 47r^2 + 48r][r^2(2r \\ \quad + 1)(9r^3 + r^2 - 12r - 6)k - (2+3r)(35r^4 + 20r^3 - 47r^2 - 48r - 12)] \end{array}\right) \quad \text{and}$$

$$\vartheta_u = \left(\begin{array}{l} -r^8(9r^3 + r^2 - 12r - 6)(1-r)^2(2r+1)^3k^4 + 2r^6(2r+1)(390r^8 \\ \quad - 210r^7 - 1201r^6 + 116r^5 + 1419r^4 + 430r^3 - 555r^2 \\ \quad - 384r - 69)k^3 - r^4(216r^{11} + 13802r^{10} + 5271r^9 - 52381r^8 - 44668r^7 \\ \quad + 56358r^6 + 86007r^5 + 9775r^4 - 43066r^3 \\ \quad - 31930r^2 - 9360r - 1032)k^2 + 2r^2(-12 - 48r - 47r^2 + 20r^3 \\ \quad + 35r^4)(36r^8 + 842r^7 + 327r^6 - 2184r^5 - 1950r^4 \\ \quad + 950r^3 + 1895r^2 + 864r + 132)k - 2(2+3r)(r^4 + 13r^3 - r^2 \\ \quad - 15r - 6)(35r^4 + 20r^3 - 47r^2 - 48r - 12)^2 \end{array}\right).$$

## Appendix B

## Proofs

### *Proof of lemma 1*

We set $M_{1b} = -2(r+1)k + 3r + 2][(2r+1)k^2 + (3r+2)(1-2k)$ and $M_{2b} = (2r^3 + 7r^2 + 10r + 4)k^2 - (4r^3 + 8r^2 + 10r + 4)k + 3r^3 + 2r^2$. We can prove $A_{0b} > 0$, $A_{1b} > 0$, $M_{1b} > 0$ and $M_{2b} > (<)0$ if $k < (>)k_b(r)$ (where $k_b(r) = (2r^3 + 4r^2 + 5r + 2 - \sqrt{(2r+1)(r+1)(1+r-r^2)(r+2)^2}/(2r^3 + 7r^2 + 10r + 4)) \in (0, 0.5)$). Thus, $(\partial h_0/\partial h_j) = (\partial R(h_1, h_2)/\partial h_j) = ((r+1)^2 r^3(1-k)/A_{0b}) > 0$, $(\partial h_j/\partial h_0) = (\partial R(h_0, h_l)/\partial h_0) = ((1-k)(r+1)^2 r^3 M_{1b}/A_{1b}) > 0$ and $(\partial h_j/\partial h_l) = (\partial R(h_0, h_l)/\partial h_l) = (r(r+1)^2(3r+2)(1-k)M_{2b}/A_{1b}) > (<)0$ if $k < (>)k_b(r)$ $(j,\ l = 1, 2,\ j \neq l)$.

### *Proof of lemma 2*

We can obtain $p_0^B = ((1-r)\beta_{0b}w/2\vartheta_b)$, $p_1^B = p_2^B = ((1-r)\beta_{1b}w/2\vartheta_b)$, $Q^B = (\lambda_b w/2(2r+1)\vartheta_b)$, $y_0^B = (r^2(1-r^2)\alpha_{0b}w/\vartheta_b)$, $y_1^B = y_2^B = (r^2(1-r^2)\alpha_{1b}w/\vartheta_b)$, $E^B = (\varsigma_b w/2(2r+1)\vartheta_b)$, where $\beta_{0b}$, $\beta_{1b}$, $\lambda_b$, $\alpha_{0b}$, $\alpha_{1b}$, $\alpha_b$, $\varsigma_b$ and $\vartheta_b$ are given in appendix A. Then, we can prove:

(i) $(\partial p_0^B/\partial k) = ((1-r)(\beta_{0b}{}'\vartheta_b - \beta_{0b}\vartheta_b{}')w/2\vartheta_b^2) > 0$ and $(\partial p_1^B/\partial k) = (\partial p_2^B/\partial k) = ((1-r)(\beta_{1b}{}'\vartheta_b - \beta_{1b}\vartheta_b{}')w/2\vartheta_b^2) > 0$;

(ii) $(\partial Q^B/\partial k) = ((1-r)(\lambda_b{}'\vartheta_b - \lambda_b\vartheta_b{}')w/2(2r+1)\vartheta_b^2) < 0$;

(iii) $(\partial y_0^B/\partial k) = (r^2(1-r^2)(\alpha_{0b}{}'\vartheta_b - \alpha_{0b}\vartheta_b{}')w/\vartheta_b^2) > 0$ and $(\partial y_1^B/\partial k) = (\partial y_2^B/\partial k) = (r^2(1-r^2)(\alpha_{1b}{}'\vartheta_b - \alpha_{1b}\vartheta_b{}')w/\vartheta_b^2) > (<)0$ if $k < (>)k_{1b}(r)$ (where $k_{1b}(r)$ satisfies $0 < k_{1b}(r) < 0.5$ and $(\alpha_{1b}{}'\vartheta_b - \vartheta_b{}'\alpha_{1b})|_{k=k_{1b}(r)} = 0$);

(iv) $(\partial(E^B)/\partial k) = ((\varsigma_b{}'\vartheta_b - \varsigma_b\vartheta_b{}')w/2(2r+1)\vartheta_b^2) < 0$.

### Proof of proposition 1

(i) We can show that $\vartheta_b > 0$, $r^2(1-k)(1-r^2)\Phi_b > 0$ and $r^2(1-k)(1-r^2)[(2r+1)k^2+(3r+2)(1-2k)]\psi_b > 0$ for $0 < k < 0.5$ and $0 < r < 1$. Therefore, $h_0^B > 0$ and $h_1^B = h_2^B > 0$;

(ii) $h_0^B - h_1^B = h_0^B - h_2^B = (r^2(1-k)(1-r^2)\{\Phi_b - [(2r+1)k^2+(3r+2)(1-2k)]\psi_b\}w/\vartheta_b) > 0$.

### Proof of proposition 2

(i) $(\partial h_0^B/\partial k) = (r^2(1-r^2)\{[-\Phi_b+(1-k)\Phi_b{}']\vartheta_b - (1-k)\Phi_b\vartheta_b{}'\}w/\vartheta_b{}^2) > 0$;

(ii) $(\partial h_1^B/\partial k) = (\partial h_2^B/\partial k) = (r^2(1-r^2)Lw/\vartheta_b{}^2)$, where $L = \left(\begin{array}{l} [(2r+1)(2-3k)k \\ \quad +(3r+2)(-3 \\ \quad +4k)]\psi_b\vartheta_b+(1 \\ \quad -k)[(2r+1)k^2 \\ \quad +(3r+2)(1-2k)] \\ \quad (\psi_b{}'\vartheta_b+\psi_b\vartheta_b{}') \end{array}\right)$.

There exists $\bar{k}(r)$ ($\bar{k}(r)$ meets $L|_{k=\bar{k}(r)} = 0$) making $L > (<)0$ if $0 < k < \bar{k}(r)$ ($\bar{k}(r) < k < 0.5$). Thus, $(\partial h_j^B/\partial k) > (<)\ 0$ $(j = 1, 2)$ if $0 < k < \bar{k}(r)$ ($\bar{k}(r) < k < 0.5$).

### Proof of proposition 3

(i) From (13), we can obtain $D^B = (Z_b{}^2dw^2/8(2r+1)^2\vartheta_b{}^2)$ where $Z_b$ is given in appendix A. Then, we obtain $(\partial D^B/\partial k) = (Z_b(Z_b{}'\vartheta_b - Z_b\vartheta_b{}')dw^2/4(2r+1)^2\vartheta_b{}^3) < 0$;

(ii) From (14), we can obtain $SW^B = ((G_b - Z_b{}^2d)w^2/8(2r+1)^2\vartheta_b{}^2)$ where $G_b$ is given in appendix A. Then, we obtain $(\partial SW^B/\partial k) = ([2(Z_b{}^2\vartheta_b{}' - Z_bZ_b{}'\vartheta_b)d - (2G_b\vartheta_b{}' - G_b{}'\vartheta_b)]w^2/8(2r+1)^2\vartheta_b{}^3)$. We can prove that $\vartheta_b > 0$, $Z_b{}^2\vartheta_b{}' - Z_bZ_b{}'\vartheta_b > 0$ and $2G_b\vartheta_b{}' - G_b{}'\vartheta_b > 0$. We set $\bar{d}(r,k) = ((2G_b\vartheta_b{}' - G_b{}'\vartheta_b)/2(Z_b{}^2\vartheta_b{}' - Z_bZ_b{}'\vartheta_b))$ and thus obtain $(\partial SW^B/\partial k) < (>)0$ if $d < (>)\bar{d}(r,k)$.

### Proof of proposition 4

(i) Because $\vartheta_u > 0$, $r^2(1-r^2)(kr+4+6r)\Phi_u > 0$, $r^2(1-r^2)\psi_u > 0$ and $r^2(k+2)(1-k)(1-r^2)\rho_u > 0$ for $0 < k < 0.5$ and $0 < r < 1$, $h_0^U > 0$, $h_1^U > 0$ and $h_2^U > 0$;

(ii) $h_0^U - h_2^U = (r^2(1-r^2)[(kr+4+6r)\Phi_u - (k+2)(1-k)\rho_u]w/\vartheta_u) > 0$ and $h_1^U - h_0^U = (r^2(1-r^2)[\psi_u - (kr+4+6r)\Phi_u]w/\vartheta_u) > 0$;

(iii) Because $(h_1^U - h_0^U) - (h_0^U - h_2^U) = (r^2(1-r^2)[\psi_u + (k+2)(1-k)\rho_u - 2(kr+4+6r)\Phi_u]w/\vartheta_u) < 0$, $h_1^U - h_0^U < h_0^U - h_2^U$.

### Proof of proposition 5

(i) $(\partial h_0^U/\partial k) = (r^2(1-r^2)[r\Phi_u\vartheta_u + (kr+4+6r)(\Phi_u{}'\vartheta_u - \Phi_u\vartheta_u{}')]w/\vartheta_u{}^2) > 0$;

(ii) $(\partial h_1^U/\partial k) = (r^2(1-r^2)(\psi_u{}'\vartheta_u - \psi_u\vartheta_u{}')w/\vartheta_u{}^2) > 0$;

(iii) $(\partial h_2^U/\partial k) = (r^2(1-r^2)[-(2k+1)\rho_u\vartheta_u + (k+2)(1-k)(\rho_u{}'\vartheta_u - \rho_u\vartheta_u{}')]w/\vartheta_u{}^2) < 0$.

### Proof of proposition 6

(i) $h_0^B - h_0^U = (r^2(1-r^2)[(1-k)\Phi_b\vartheta_u - (kr+4+6r)\Phi_u\vartheta_b]w/\vartheta_b\vartheta_u) > 0$;

(ii) $h_1^B - h_1^U = (r^2(1-r^2)\{(1-k)[(2r+1)k^2 + (3r+2)(1-2k)]\psi_b\vartheta_u - \psi_u\vartheta_b\}w/\vartheta_b\vartheta_u) < 0$;

(iii) We can obtain $h_2^B - h_2^U = (r^2(1-r^2)(1-k)\{[(2r+1)k^2 + (3r+2)(1-2k)]\psi_b\vartheta_u - (k+2)\rho_u\vartheta_b\}w/\vartheta_b\vartheta_u)$. When $\tilde{r} < r < 1$ ($\tilde{r} \approx 0.434$), $h_2^B - h_2^U > 0$. In addition, when $0 < r < \tilde{r}$, there exists $\tilde{k}(r)$ ($\tilde{k}(r)$ satisfies $0 < \tilde{k}(r) < 0.5$ and $(h_2^B - h_2^U)|_{k=\tilde{k}(r)} = 0$) making $h_2^B - h_2^U > (<) 0$ if $k < (>) \tilde{k}(r)$.

## Proof of proposition 7

(i) $D^B - D^U = (({Z_b}^2{\vartheta_u}^2 - 4Z_u^2{\vartheta_b}^2)dw^2/8(2r+1)^2{\vartheta_b}^2{\vartheta_u}^2) < 0$;

(ii) We can obtain $SW^B - SW^U = ([(4Z_u^2{\vartheta_b}^2 - Z_b^2{\vartheta_u}^2)d - (4G_u{\vartheta_b}^2 - G_b{\vartheta_u}^2)]w^2/8(2r+1)^2{\vartheta_b}^2{\vartheta_u}^2)$. We can prove that $4Z_u^2{\vartheta_b}^2 - Z_b^2{\vartheta_u}^2 > 0$ and $4G_u{\vartheta_b}^2 - G_b{\vartheta_u}^2 > 0$. We set $\breve{d}(r,k) = ((4G_u{\vartheta_b}^2 - G_b{\vartheta_u}^2)/(4Z_u^2{\vartheta_b}^2 - Z_b^2{\vartheta_u}^2))$. Obviously, $\breve{d}(r,k) > 0$. Then, we obtain $SW^B - SW^U > (<) 0$ if $d > (<) \breve{d}(r,k)$.

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