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Common Ownership and Environmental Corporate Social Responsibility*

Kosuke Hirose† and Toshihiro Matsumura‡

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Abstract

We theoretically investigate how common ownership (or the extent of collusion in an industry) affects firms' voluntary commitment with emission restrictions and emissions abatement activities in an oligopoly. We find that common ownership reduces emissions by reducing output, and may stimulate emissions abatement activities if the degree of common ownership is small. However, significant common ownership always reduces emissions abatement activities. Additionally, common ownership may or may not improve welfare, depending on the implicit carbon cost.

JEL classification codes: M14, Q57, L13

Keywords: corporate social responsibility, anticompetitive effect, voluntary emissions cap, emissions abatement

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Highlights

Firms' voluntary commitment with emission restrictions are investigated.

Common ownership affects firms' environmental activities.

Common ownership likely reduces emissions but may reduce emission abatement.

Moderate levels of common ownership improve welfare with high emission costs.

Significant levels of common ownership harm welfare.

1 Introduction

Climate change is one of the most serious risks confronting society, and reducing CO2 emissions is an increasingly important policy issue. The basic policy for reducing CO2 emissions is the introduction of market-based instruments such as carbon (emissions) taxes and tradable permits (Pigou,1932; Baumol and Oates, 1988) or mandatory regulations such as emission-intensity or energy-conservation regulations (Helfand, 1991; Holland et al., 2009; Matsumura and Yamagishi, 2017). However, firms' voluntary activities to reduce CO2 emissions are also critical for achieving a net-zero emission society.[1]

Corporate activities that go beyond the legal or regulatory requirements are generally labeled Corporate Social Responsibility (CSR) or Environmental, Social, and Governance (ESG) activities. According to the Governance & Accountability Institute, 90 percent of S&P 500 companies published corporate sustainability reports in 2019.[2] These voluntary actions for reducing CO2 emissions attract attention from academic researchers, policy makers, and investors (Lyon and Maxwell, 2004; Kitzmueller and Shimshack, 2012; Poyago-Theotoky and Yong, 2019; Lee and Park, 2019). Notably, investors' interest in CSR and ESG is evident. During 2020, U.S. sustainable funds received \$51 billion in net flows, a significant increase from the 2019 flows of \$21.4 billion and about 10 times the 2018 flows of \$5.4 billion.[3] Some empirical works suggest that the financial performance of firms believed to be highly concerned with environmental CSR is relatively higher (Margolis et al., 2007), and thus investors' pressure may stem from their profit-maximizing motives (Hirose et al., 2020).

[1] Holland (2012) and Hirose and Matsumura (2020) compare environmental policies from the welfare perspective. See Ino and Matsumura (2021a,b) for a combination of market-based instruments and regulations. See Vogel (2005), McWilliams et al. (2006), and Calveras et al. (2007) for the advantages of a voluntary approach.

[2] https://www.ga-institute.com/research/ga-research-collection/sustainability-reporting-trends/2020-russell-1000-flash-report.html

[3] https://www.morningstar.com/articles/1019195/a-broken-record-flows-for-us-sustainable-funds-again-reach-new-heights

Another distinct feature of recent financial markets is the high concentration of the investment industry. The growth of financial markets led the same set of institutional investors, such as Vanguard, BlackRock, State Street, and Fidelity, to hold substantial shares in major listed firms that compete in the same industries (common ownership).[4] If these firms are concerned about the interests of these common owners, then they are indirectly concerned about other firms' profits. Hence, they may deviate from profit-maximizing behavior.[5]

In this study, we investigate how common ownership affects voluntary emission restrictions and emission abatement investments (which we call environmental CSR). As Hirose et al. (2020) show, profit-maximizing firms may voluntarily commit to an effective upper limit of emissions to soften competition and raise prices. However, the effect of common ownership is ambiguous. On the one hand, an increase in common ownership softens competition and raises prices, and thus firms may lose their incentive to raise their prices by implementing voluntary emissions restrictions. On the other hand, an increase in common ownership internalizes the positive rivals' profit-raising effect of an environmental commitment. Therefore, it may increase the incentive for environmental CSR.

We show that the former effect dominates the latter effect and thus reduces the equilibrium abatement investment level under a high degree of common ownership. However, the latter effect can be stronger than the former effect if the degree of common ownership is small. Thus, common ownership may increase the equilibrium abatement investment. Our result suggests that a significant amount of common ownership harms environmental efficiency (increases the emissions per output), while a moderate amount of common ownership may be beneficial. We also show that the common ownership may or may not improve

[4]BlackRock, Vanguard, and State Street, the top three institutional investors, own more than 10% of the shares in listed firms globally and are often the largest stockholders in many listed firms (Nikkei Market News, 2018/10/24).

[5]In addition, several firms in the same industry hold minor shares in each other (cross-shareholding); see Reynolds and Snapp (1986), Farrell and Shapiro (1990), and Gilo et al. (2006).

welfare, depending on the social costs of emissions.

This study is related to the literature on voluntary activities and CSR. A seminal question is why firms voluntarily engage in CSR. If consumers reward firms for their environmental CSR, then firms increase the demand for their products and thereby earn higher profits (McWilliams and Siegel, 2001; Baron, 2008; and Liu et al., 2015). Graff Zivin and Small (2005) provide a model in which investors have preferences for both financial and social returns and can invest in firms that engage in CSR. If CSR and personal giving are imperfect substitutes, then a positive level of CSR is necessary to maximize shareholder value. Lambertini and Tampieri (2015) and Fukuda and Ouchida (2020) analyze models with firms having social concerns in their objective, in the context of strategic CSR developed by Baron (2001). As Maxwell et al. (2000) and Egorov and Harstad (2017) argue, firms can use CSR to avoid future government regulations or activist boycotts. Hirose et al. (2020) find that cooperative CSR through an industry association enhances CSR activities, and firms may even individually adopt CSR to relax market competition. In response to the high market concentration we see in the current financial market, we examine the effects of common ownership on CSR activities, which is not discussed in the literature.

Our study is also related to the growing literature on common ownership. This common, or overlapping, ownership among competing firms may affect their behavior and yield anticompetitive outcomes. Thus, common ownership is now a central issue in recent debates on antitrust policies. Some empirical studies show that it has a substantial effect on the strategic behavior of firms held by institutional stockholders.[6]

While common ownership softens competition in product or service markets and raises prices, partial ownership by common owners in the same industry may lead firms to internalize industry-wide externalities and improve welfare. López and Vives (2019) show a

[6] See Backus et al. (2019) for an example of the rise in common ownership in the U.S., and Schmalz (2018) for a review of empirical studies that suggests links between common ownership and firms' behavior. For antitrust concerns, see Elhauge (2016).

possible inverted relationship between the degree of common ownership and welfare. Common ownership internalizes the positive externality of R&D. This welfare-improving effect may dominate the welfare-harming competition-reducing effect when the degree of common ownership is not too large. Sato and Matsumura (2020) investigate a free entry market and find that common ownership internalizes the business-stealing effect and thus moderate common ownership may improve welfare.[7] They also show that significant common ownership always reduces welfare. Chen et al. (2021) investigate a vertically related market. They demonstrate that common ownership mitigates the problem of double marginalization and this welfare-improving effect dominates the welfare-harming competition-reducing effect in the downstream market if the competition among downstream firms is weak. However, no study analyzes the relationship between common ownership and environmental CSR.

The rest of this paper is organized as follows. Section 2 presents the basic model. Section 3 provides the equilibrium analysis and welfare implications. Finally, Section 4 concludes the paper. We provide the proofs in the appendix.

2 The Model

We formulate a duopoly model in which each firm i ($i = 1, 2$) voluntary commits to an emissions cap of E_i and then chooses its price p_i in the product market. We assume a standard differentiated duopoly with linear demand (Dixit, 1979). The quasi–linear utility function of the representative consumer is $U(q_i, q_j) = \alpha(q_i + q_j) - \beta(q_i^2 + 2\delta q_i q_j + q_j^2)/2 + y$, where y is the numeraire. The parameters α and β are positive constants, and $\delta \in (0, 1)$ represents the degree of product differentiation, where a smaller δ indicates a higher degree of product differentiation. Products are differentiated and the demand function is given as

$$q_i = \frac{\alpha(1-\delta) - p_i + \delta p_j}{\beta(1-\delta^2)}, \tag{1}$$

[7]For a discussion on the business-stealing effect in free entry markets, see Mankiw and Whinston (1986).

where q_i is firm i's output and represents the degree of product differentiation. The output q_i generates emissions of hq_i. Firm i's emission e_i is $hq_i - x_i$, where x_i is firm i's emission abatement. To meet the commitment of the upper limit E_i, firm i engages in abatement activity $x_i = \max\{0, hq_i - E_i\}$. We consider that firms adopt environmental CSR if and only if the constraint is binding and the resulting abatement level is non-zero. The damage from emissions, D, is $r(e_i + e_j)^2/2$. The abatement cost is $kx_i^2/2$. We assume a constant marginal production cost and normalize it to zero.

Firm i's profit π_i is $\pi_i = p_i q_i - kx_i^2/2$. As long as the commitment is binding (i.e., $x_i > 0$), $\pi_i = p_i q_i - k(hq_i - E_i)^2/2$. If the commitment is non-binding, then $\pi_i = p_i q_i$.

Following the recent theoretical literature on common ownership (López and Vives, 2019), we assume that each firm i has the following objective function

$$\psi_i = \pi_i + \lambda \pi_j,$$

where π_i is firm i's profit, π_j is its rival's profit, and λ is the degree of common ownership.[8]

3 Analysis

We solve the game by backward induction. In the second stage, given E_i and E_j, each firm i chooses p_i independently. The first-order condition is[9]

$$\begin{aligned}\frac{\partial \psi_i}{\partial p_i} = & \frac{(1-\delta)\alpha - 2p_i + \delta p_j}{\beta(1-\delta^2)} + \frac{kh}{\beta(1-\delta^2)} \left(h\frac{\alpha(1-\delta) - p_i + \delta p_j}{\beta(1-\delta^2)} - E_i \right) \\ & + \lambda \left\{ \frac{\delta p_j}{\beta(1-\delta^2)} - \frac{kh\delta}{\beta(1-\delta^2)} \left(h\frac{\alpha(1-\delta) - p_j + \delta p_i}{\beta(1-\delta^2)} - E_j \right) \right\} = 0.\end{aligned} \tag{2}$$

From (2), we obtain the equilibrium prices $p_i^S(E_i, E_j)$ $(i = 1, 2, i \neq j)$, where superscript S denotes the second-stage equilibrium. We thus obtain $x_i^S = hq_i(p_i^S, p_j^S) - E_i$.

[8] Prior studies also investigate this type of payoff interdependence in using a coefficient of cooperation model (Cyert and Degroot, 1973; Escrihuela-Villar, 2015) and relative-profit maximization model (Matsumura and Matsushima, 2012; Matsumura et al., 2013; Escrihuela-Villar and Gutiérrez-Hita, 2019; Hamamura, 2021).

[9] Without common ownership (i.e., when $\lambda = 0$), the constraint $E_i \leq e_i$ is binding in equilibrium (Hirose et al., 2020). This is true for $\lambda \in (0, 1)$. Therefore, we need not consider the non-binding case.

Differentiating (2) leads to

$$\begin{aligned}\frac{\partial p_i^S}{\partial E_i} &= -\frac{\beta kh\left\{\beta(1-\delta^2)(2-\lambda\delta^2-\lambda)\delta + kh^2(1-\lambda^2\delta^2)\right\}}{\beta^2(1-\delta^2)(4-(1+\lambda)^2\delta^2)+2\beta kh^2(2-(1+\lambda^2)\delta^2)+k^2h^4(1-\lambda^2\delta^2)} < 0,\\ \frac{\partial p_j^S}{\partial E_i} &= -\frac{\beta kh\left\{\beta(1-\delta^2)(1-\lambda)\delta + kh^2\delta(1-\lambda^2\delta^2)\right\}}{\beta^2(1-\delta^2)(4-(1+\lambda)^2\delta^2)+2\beta kh^2(2-(1+\lambda^2)\delta^2)+k^2h^4(1-\lambda^2\delta^2)} < 0.\end{aligned} \tag{3}$$

In the first stage, each firm i chooses E_i independently. The first-order condition is

$$\frac{\partial \psi_i}{\partial p_j}\frac{\partial p_j^S}{\partial E_i} + \frac{\partial \psi_i}{\partial E_i} = 0, \tag{4}$$

where

$$\begin{aligned}\frac{\partial \psi_i}{\partial p_j} &= \frac{\delta p_i^S}{\beta(1-\delta^2)} - \frac{kh\delta}{\beta(1-\delta^2)}\left(h\frac{\alpha(1-\delta)-p_j^S+\delta p_i^S}{\beta(1-\delta^2)} - E_i\right)\\ &\quad + \lambda\left\{\frac{(1-\delta)\alpha - 2p_j^S + \delta p_i^S}{\beta(1-\delta^2)} + \frac{kh}{\beta(1-\delta^2)}\left(h\frac{\alpha(1-\delta)-p_j^S+\delta p_i^S}{\beta(1-\delta^2)} - E_i\right)\right\},\\ \frac{\partial \psi_i}{\partial E_i} &= k\left(h\frac{\alpha(1-\delta)-p_i^S+\delta p_j^S}{\beta(1-\delta^2)} - E_i\right).\end{aligned}$$

From (4), we obtain the equilibrium emissions cap, E^F where superscript F denotes the first-stage equilibrium and we omit the subscript because $E_i^F = E_j^F$. We then have

$$E^F = \frac{\alpha\left\{kh(1-\lambda\delta) - (1-\lambda^2)\delta(\partial p_j^S/\partial E_i)\right\}}{k\left\{\beta(1+\delta)(2-\delta-\lambda\delta) - h(1-\lambda^2)\delta(\partial p_j^S/\partial E_i)\right\}}. \tag{5}$$

Firms voluntary restrict their emissions for any $\lambda \in [0,1)$. That is, firms that have common ownership always adopt environmental CSR. From (5), we obtain the following Proposition.

Proposition 1 *The equilibrium emissions level E^F is decreasing in λ if λ is sufficiently close to zero or one.*

Proof See the Appendix.

A marginal increase in common ownership from $\lambda = 0$ leads to more environmental CSR. However, we fail to derive a clear property on whether an increase in λ increases or decreases E^F for $\lambda \in (0,1)$. Here, we present some numerical results. Suppose that $\alpha = 10, \beta = 2, k = 2$, and $h = 1$. Figure 1 illustrates the region in which $dE^F/d\lambda < 0$.

Unless both δ and λ are large, an increase in the degree of common ownership reduces the equilibrium emissions level. As in Figure 1, the region in which $dE^F/d\lambda < 0$ expands as h increases.

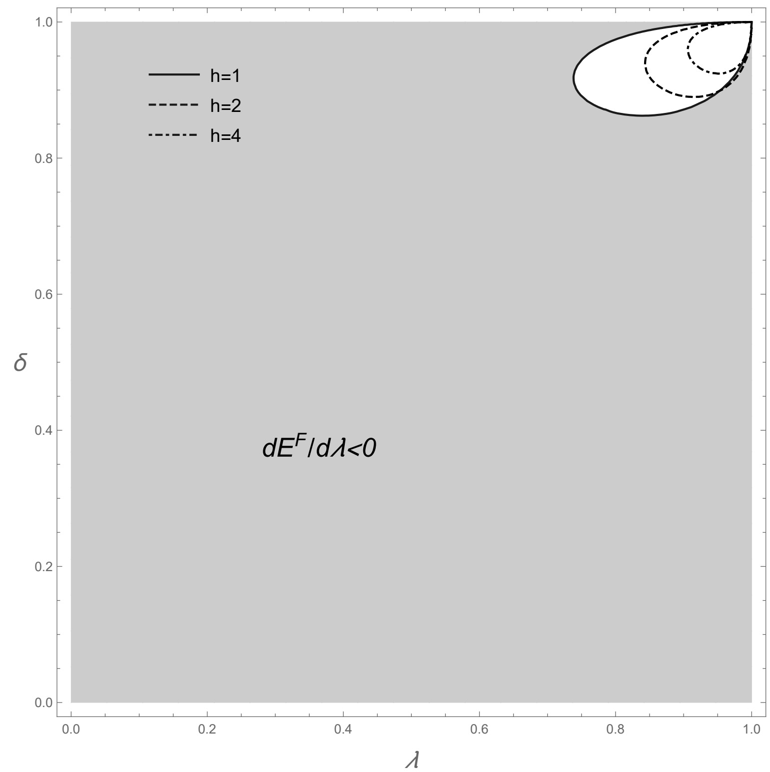


Figure 1: ($\alpha = 10$, $\beta = 2$, and $k = 2$)

Figure 1 illustrates that unless both δ and λ are close to 1, an increase in λ (an increase in the degree of collusion) reduces emissions. There are two channels through which emissions decrease: a reduced output level or the increased emissions abatement investments. The increase in emissions abatement investments improves the emission efficiency (i.e., reduces the emissions per output), while the decrease in output does not.

We now take a close look at these two effects to understand the intuition behind this result. From (2) and (5), we obtain

$$p^F = \frac{\alpha(\beta(1-\delta^2) - h\delta(1-\lambda^2)(\partial p_j^S/\partial E_i))}{\beta(1+\delta)(2-\delta-\lambda\delta) - h\delta(1-\lambda^2)\partial p_j^S/\partial E_i)}. \tag{6}$$

Substituting (6) into (1), we obtain

$$q^F = \frac{\alpha(1-\delta\lambda)}{\beta(1+\delta)(2-\delta-\lambda\delta) - h\delta(1-\lambda^2)(\partial p_j^S/\partial E_i)}. \tag{7}$$

From (7), we derive the following Proposition.

Proposition 2 *The equilibrium output level q^F is decreasing in λ.*

Proof See the Appendix.

Proposition 2 states that common ownership leads to a collusive output level, which reduces emission. As we state above, this result is natural and intuitive. Because of this effect, an increase in λ reduces the equilibrium emissions for wide range of parameter values. However, an increase in λ may increase the equilibrium emissions, implying that another effect can increase emissions. In other words, an increase in λ can reduce the resulting abatement investments.

We next discuss the relationship between λ and x^F. Using (5) and (7), we obtain

$$x^F = \frac{\alpha\delta(\lambda^2-1)(\partial p_j^S/\partial E_i)}{k\left\{\beta(1+\delta)(2-\delta-\lambda\delta) - h\delta(1-\lambda^2)(\partial p_j^S/\partial E_i)\right\}}. \tag{8}$$

From (8), we derive the following proposition.

Proposition 3 *(i) The equilibrium abatement level x^F is decreasing in λ if $\lambda \in (\frac{2-\delta-2\sqrt{1-\delta}}{\delta}, 1]$.*
(ii) $(dx^F/d\lambda)|_{\lambda=0} > 0$ if $\delta > \frac{\sqrt{17}-1}{4} \approx 0.7807$.

Proof See the Appendix.

Proposition 3 suggests that x^F may increase with λ if λ is small (close to zero), whereas x^F always decreases with λ if λ is large (close to one). In other words, a moderate degree of common ownership may accelerate emissions abatement activities but a significant degree of common ownership dampens these activities. We explain the intuition.

An increase in emissions abatement investment by a firm's stricter environmental commitment (smaller E_i) raises its marginal cost, which raises the prices for the focal firm and its rival through the strategic interaction in the product market. The increase in the equilibrium prices increases the profit for both the focal firm and its rival. Each firm is more concerned with the rival's profit when λ is larger, and thus an increase in λ may increase x^F, because a stricter commitment raises the rival's profit.

However, when λ is sufficiently large, firms can collude without committing to an emissions cap. Thus, when λ is sufficiently large, firms avoid stricter commitments that induce a larger x^F to save the abatement investment costs. Therefore, x^F is decreasing in λ when λ is large.

Similarly, when δ is smaller (i.e., products are more differentiated), firms can more easily collude without committing to an emissions cap, and thus firms avoid stricter commitments that induce larger x^F to save the abatement investment costs. Therefore, x^F is always decreasing in λ when δ is small.

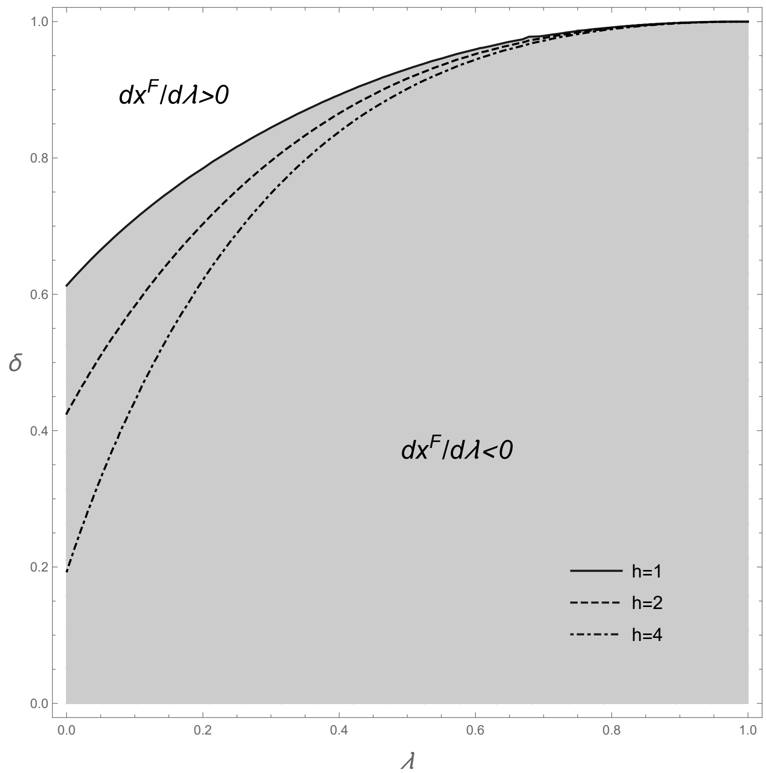


Figure 2: ($\alpha = 10$, $\beta = 2$, and $k = 2$)

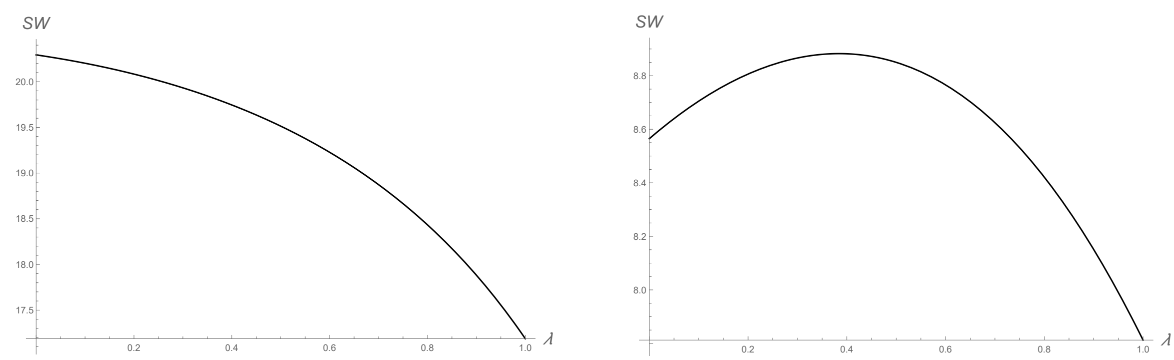
Figure 2 illustrates the region in which $dx^F/d\lambda > 0$. When λ is small, $dx^F/d\lambda > 0$, unless δ is small. However, the region in which $dx^F/d\lambda > 0$ shrinks as λ increases, and the region disappears when λ is close to one. As Figure 1 suggests, the emissions level is decreasing in λ for most of the region, but Figure 2 suggests that this occurs because the output level decreases rather than due to an increase in environmental investment. Therefore, common ownership, especially a large degree of common ownership, is harmful for stimulating emissions abatement investments.

Finally, we discuss welfare implications. Welfare is consumer surplus plus the firms' profits minus damage due to emissions. In symmetric equilibrium, it equals

$$W(\lambda) = 2\alpha q^F - \beta(1+\delta)(q^F)^2 - k(x^F)^2 - 2r(E^F)^2. \tag{9}$$

Using numerical simulations, we show that whether an increase in λ improves welfare depends on the significance of the cost of social damage, measured by r (See Figure 3). Welfare is decreasing in λ when r is small because an increase in λ reduces consumer surplus significantly because output declines. However, when r is large, welfare can be nonmonotone.

We explain the intuition. An increase in λ reduces the production level, which also reduces emissions and improves welfare. This welfare-improving effect dominates the welfare-reducing effect mentioned above when r is large. When λ is smaller and r is larger, this welfare-improving common ownership is more likely because the consumer-surplus-reducing effect is weaker and the welfare-improving effect of reducing emissions is stronger. Thus, the relationship between λ and welfare can be inverted-U shaped when r is large.



$r = 2$ $\qquad\qquad$ $r = 5$

Figure 3: $dW/d\lambda$ ($\alpha = 10$, $\beta = 2$, $k = 2$, $h = 1$, and $\delta = 6/10$)

4 Concluding Remarks

In this study, we investigate how common ownership affects emissions levels when firms can use environmental CSR as a commitment device to soften competition. We show that the resulting emissions level is decreasing in the degree of common ownership under moderate conditions. However, an increase in the degree of common ownership reduces emissions abatement investment unless the degree of common ownership is small. Thus, common ownership, especially a significant degree of common ownership, dampens emissions abatement investments. We can interpret the degree of common ownership as a measure of collusion in an industry. Thus, our results suggest that collusion in an industry reduces emissions mainly because collusion reduces output, not because collusion stimulates emissions abatement investments, especially when the collusion is strong.

In this study, we assume that firms are profit-maximizers and they adopt environmental CSR to increase their own profits. However, firms may do so for non-profit-related motivations. Extending our analysis in this direction remains for future research.

Appendix

Proof of Proposition 1

We have

$$\left.\frac{\partial E^F}{\partial \lambda}\right|_{\lambda=0} = -\frac{\alpha\delta h\left\{k^4h^8+\beta^4(1-\delta)^2(1+\delta)^3B_1+\beta^3kh^2(1+\delta)^2B_2+\beta^2k^2h^4B_3+\beta k^3h^6B_4\right\}}{\beta\left\{\beta^2\left(2+\delta-\delta^2\right)^2\left(2-\delta-\delta^2\right)+\beta kh^2\left(\delta^4-2\delta^3-7\delta^2+4\delta+8\right)+k^2h^4(2+\delta)\right\}^2},$$

where

$$\begin{aligned}
B_1 &= 16-24\delta+14\delta^3-3\delta^4-\delta^5>0,\\
B_2 &= 32-76\delta+40\delta^2+35\delta^3-38\delta^4+4\delta^5+3\delta^6>0,\\
B_3 &= 24-6\delta-38\delta^2+16\delta^3+19\delta^4-8\delta^5-3\delta^6>0,\\
B_4 &= 8-\delta-6\delta^2+2\delta^3+\delta^4>0.
\end{aligned}$$

Thus,

$$\left.\frac{\partial E^F}{\partial \lambda}\right|_{\lambda=0}<0,$$

which implies that E^F is decreasing in λ if λ is sufficiently close to zero.

We also have

$$\left.\frac{\partial E^F}{\partial \lambda}\right|_{\lambda=1} = -\frac{\alpha\delta h(kh^2+2\beta(1+\delta))}{4\beta(kh^2+2\beta(1-\delta))(1+\delta)^2}<0,$$

which implies that E^F is decreasing in λ if λ is sufficiently close to one. ■

Proof of Proposition 2

From (3), we obtain

$$\frac{\partial^2 p_j^S}{\partial E_i\partial\lambda} = \frac{\beta kh\delta(1-\delta^2)H(\lambda)}{\left\{\beta^2(1-\delta^2)(4-(1+\lambda)^2\delta^2)+2\beta kh^2(2-(1+\lambda^2)\delta^2)+k^2h^4(1-\lambda^2\delta^2)\right\}^2}, \quad (10)$$

where $H(\lambda)=\beta^2(1-\delta^2)(4-\delta^2(-\lambda^2+2\lambda+3))+2\beta\gamma(1-\delta^2)h^2(\delta^2\lambda^2+\delta^2\lambda+2)+\gamma^2h^4(\delta^2\lambda^2+2\delta^2\lambda+1)>0$.

Differentiating (7) yields

$$\frac{\partial q^F}{\partial \lambda} = -\frac{\alpha\delta\left\{\beta(1-\delta^2) + h(2\lambda-\delta-\lambda^2\delta)(\partial p_j^S/\partial E_i) - h(1-\lambda^2)(1-\lambda\delta)\left(\partial^2 p_j^S/\partial E_i \partial\lambda\right)\right\}}{\left\{\beta(1+\delta)(2-\delta-\lambda\delta) - h\delta(1-\lambda^2)(\partial p_j^S/\partial E_i)\right\}^2}. \tag{11}$$

From (3) and (10), the numerator in (11) is

$$\frac{\beta F(\lambda)}{\left\{\beta^2(1-\delta^2)(4-(1+\lambda)^2\delta^2) + 2\beta k h^2(2-(1+\lambda^2)\delta^2) + k^2h^4(1-\lambda^2\delta^2)\right\}^2}, \tag{12}$$

where

$$\begin{aligned} F(\lambda) &= h^8k^4(1-\delta\lambda)^4(\delta\lambda+1)^2 + \beta^4\left(1-\delta^2\right)^3\left(4-\delta^2(\lambda+1)^2\right)^2 \\ &\quad + \beta^3(1-\delta^2)^2h^2kF_1 + \beta^2\left(1-\delta^2\right)h^4k^2F_2 + \beta h^6k^3F_3 \end{aligned} \tag{13}$$

$$\begin{aligned} F_1 &= \delta^4(1+\lambda)^2\left(7\lambda^2-2\lambda+3\right) - \delta^3(\lambda+1)^2\left(\lambda^2+2\lambda-3\right) \\ &\quad - 4\delta^2\left(2\lambda^3+5\lambda^2+4\lambda+5\right) + 4\delta\left(3\lambda^2-2\lambda-1\right) + 32 > 0, \\ F_2 &= \delta^6\lambda^2(\lambda+1)^2\left(\lambda^2+2\lambda-3\right) - 2\delta^5\lambda(\lambda+1)^2\left(\lambda^2+\lambda-1\right) - 3\delta^4\left(\lambda^4-4\lambda^3-4\lambda^2-1\right) \\ &\quad - 2\delta^3\left(\lambda^4-8\lambda^3+3\lambda^2-2\lambda-2\right) - 2\delta^2\left(4\lambda^3+9\lambda^2+2\lambda+9\right) \\ &\quad + 4\delta\left(3\lambda^2-4\lambda-1\right) + 24 > 0, \\ F_3 &= \delta^6\lambda^2\left(2\lambda^4+3\lambda^2-2\lambda-3\right) + \delta^5\lambda\left(-4\lambda^4+\lambda^3-8\lambda^2+\lambda+2\right) \\ &\quad + \delta^4\left(-5\lambda^4+4\lambda^3+8\lambda^2+1\right) + \delta^3\left(-\lambda^4+16\lambda^3-4\lambda^2+4\lambda+1\right) - \delta^2\left(2\lambda^3+7\lambda^2+7\right) \\ &\quad + \delta\left(3\lambda^2-10\lambda-1\right) + 8 > 0 \end{aligned}$$

for any $\delta \in (0,1)$, $\lambda \in [0,1]$.

These imply Proposition 2. ■

Proof of Proposition 3

(i) Differentiating (8) yields

$$\frac{\partial x^F}{\partial \lambda} = -\frac{\alpha\beta\delta(1+\delta)\left\{(2\lambda(\delta-2)+\delta+\delta\lambda^2)(\partial p_j^S/\partial E_i) + (1-\lambda^2)(2-\delta-\delta\lambda)\left(\partial^2 p_j^S/\partial E_i\partial\lambda\right)\right\}}{k\left\{\beta(1+\delta)(2-\delta-\lambda\delta) - h\delta(1-\lambda^2)(\partial p_j^S/\partial E_i)\right\}^2}. \tag{14}$$

Because $\partial p_j^S/\partial E_i < 0$ and $\partial^2 p_j^S/\partial E_i \partial\lambda > 0$, we have

$$\frac{\partial x^F}{\partial \lambda} < 0 \ \text{ if } \ 2\lambda(\delta-2)+\delta+\delta\lambda^2 < 0. \tag{15}$$

Because $2\lambda(\delta-2)+\delta+\delta\lambda^2 < 0$ if and only if $\lambda \in (\frac{2-\delta-2\sqrt{1-\delta}}{\delta}, 1]$, we obtain Proposition 3(i).

■

(ii) From (14),

$$\frac{\partial x^F}{\partial \lambda}\Big|_{\lambda=0} = \frac{\alpha\beta\delta(1+\delta)\left\{-\delta\left(\partial p_j^S/\partial E_i\big|_{\lambda=0}\right)-(2-\delta)\left(\partial^2 p_j^S/\partial E_i\partial\lambda\big|_{\lambda=0}\right)\right\}}{k\{\beta(2-\delta)(1+\delta)-h\delta\left(\partial p_j^S/\partial E_i\big|_{\lambda=0}\right)\}^2}. \tag{16}$$

If the numerator in (16) is positive, then $(\partial x^F/\partial\lambda\big|_{\lambda=0}) > 0$. Note that

$$\begin{aligned}
\frac{\partial p_j^S}{\partial E_i}\Big|_{\lambda=0} &= -\frac{\beta kh\delta\left\{\beta(1-\delta^2)+kh^2\right\}}{\beta^2(1-\delta^2)(4-\delta^2)+2\beta kh^2(2-\delta^2)+k^2h^4}, \\
\frac{\partial^2 p_j^S}{\partial E_i\partial\lambda}\Big|_{\lambda=0} &= \frac{\beta^2 kh\delta(1-\delta^2)\{\beta^2(1-\delta^2)(4-3\delta^2)+4\beta kh^2(1-\delta^2)+k^2h^4\}}{\{\beta^2(1-\delta^2)(4-\delta^2)+2\beta kh^2(2-\delta^2)+k^2h^4\}^2}.
\end{aligned}$$

We rewrite the numerator in (16) as

$$\alpha\beta\delta\left\{\frac{\beta kh\delta G(\delta)}{\left(\beta^2\left(\delta^4-5\delta^2+4\right)+2\beta k\left(2-\delta^2\right)h^2+k^2h^4\right)^2}\right\},$$

where $G(\delta) = \delta h^6k^3 + 2\beta^3(1-\delta^2)^2(-2\delta^3+3\delta^2+4\delta-4) + 2\beta(-2\delta^3+\delta^2+3\delta-1)h^4k^2 + \beta^2(7\delta^5-8\delta^4-19\delta^3+16\delta^2+12\delta-8)h^2k$. Thus,

$$\frac{\partial x^F}{\partial \lambda}\Big|_{\lambda=0} \geq (<) 0 \ \text{ if } \ G(\delta) \geq (<) 0.$$

We now show a sufficient condition for $G(\delta) > 0$. For the second, third, and fifth terms in $G(\delta)$, we have

$$\begin{cases}
-2\delta^3+3\delta^2+4\delta-4 > 0 & \Longleftrightarrow \ 0.321 \lessapprox \delta < 1, \\
-2\delta^3+\delta^2+3\delta-1 > 0 & \Longleftrightarrow \ (\sqrt{17}-1)/4 < \delta < 1, \\
7\delta^5-8\delta^4-19\delta^3+16\delta^2+12\delta-8 > 0 & \Longleftrightarrow \ 0.560 \lessapprox \delta < 1.
\end{cases} \tag{17}$$

Thus, a sufficient condition for $G(\delta) > 0$ is

$$-2\delta^3+3\delta^2+4\delta-4 > 0 \iff \delta > \frac{\sqrt{17}-1}{4} \approx 0.780. \tag{18}$$

These imply Proposition 3(ii). ■

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Declarations

Both authors declare no conflicts of interests and that there are no financial and personal relationships with other people or organizations that could inappropriately influence our work.

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