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RESEARCH ARTICLE

Strategic environmental policy in a differentiated duopoly with overlapping ownership: a welfare analysis

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Abstract

This paper analyzes strategic environmental policy when polluting firms engage in overlapping ownership arrangements (OOAs) under differentiated duopoly with quantity competition. Specifically, we focus on two pollution control instruments: emission taxes and standards. The key findings are as follows: (i) Compared to the case without ownership, the optimal environmental tax rate and absolute standard are higher (lower) when the polluting firms' products are complements (substitutes). (ii) Both the tax and standard policies are equally efficient in their effects on the firms' output and abatement decisions, consumer surplus, environmental quality, and social welfare, regardless of whether the differentiated products are complements or substitutes. (iii) If the government sets equity share and emission tax (or standard) simultaneously to maximize social welfare, the optimal equity share may exceed 50% for OOA firms producing two complements and is inversely related to the degree of product complementarity. Our results have welfare implications for the choice of environmental regulation between taxes and standards, when equity share is exogenous, or when the government determines an optimal mix of equity share and emission tax (or standard).

Keywords Environmental policy · Ownership structure · Product differentiation · Welfare implications

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1 Introduction

Among the key elements challenging the environmental sustainability of an economy include, but are not limited to, what policy instruments should strategically be implemented to improve the quality of life by reducing damage to the environment caused by pollution or waste. Firms that generate pollution or waste may financially engage in ownership arrangements with their competitors. Overlapping ownership arrangements by competing firms in oligopolistic industries are becoming increasingly prevalent, with firms holding equity stakes on rivals' profits without corporate control. Such bilateral or two-sided ownership arrangements are commonly observed in various industries, including automobiles (Alley, 1997; Ono et al. 2004), telecommunications (Parker and Röller 1997), electricity power (Amundsen and Bergman 2002), steel (Gilo et al. 2006), disposable razors (Brito et al. 2014), and airlines (Clayton and Jorgensen, 2005; Kennedy et al. 2017; Azar et al. 2018).

Despite that partial ownership stakes carry no voting rights in business operations,[1] the so-called "silent (or passive) investments" affect the output decisions of polluting firms and the amounts of pollutant emissions in production. As such, the design of environmental policies for imperfectly competitive polluting industries cannot be isolated from the ownership arrangements among competing firms holding a fraction of each other's stocks or profits.[2] Some issues of policy importance to reduce pollution and improve environmental quality naturally arise. How would the choice of environmental policy instruments between uniform emission taxes and absolute emission standards and their levels be affected by the interaction of product differentiation and overlapping ownership among polluting firms?

The study by Bárcena-Ruiz and Campo (2012) is among the first to stress the importance of considering bilateral cross-ownership arrangements when designing

[1] There is an important distinction between financial interest and corporate control in the industrial economics literature (e.g., O'Brien and Salop 2000). Our analysis focuses on the aspect of financial interest, which refers to an investment in receiving a positive share of a firm's profit without having any discretions on the firm's operations and decisions. As for corporate control, it refers to situations under which shareholders/investors can make the decisions for the firm. Researchers further analyze the competitive and anticompetitive effects of partial ownership arrangements (see, e.g., Reynolds and Snapp 1986; Farrell and Shapiro 1990; Malueg 1992; O'Brien and Salop 2000; Clayton and Jorgensen 2005; Dietzenbacher and Temurshoev 2008; and Lopez and Vives 2019).

[2] For studies on environmental policy under imperfectly competitive market, see Buchanan (1969), Adar and Griffin (1976), Barnett (1980), Levin (1985), Baumol and Oates (1988), Simpson (1995), Helfand (1999), Requate (2006), Lambertini and Tampieri (2012), and Moner and Rubio (2016), among others. In addressing pollution concern in the era of globalization, Tiba and Belaid (2020) examine how foreign direct investment (FDI) inflows and trade openness affects environmental degradation. There empirical results show the possibilities of bidirectional long-term causality between CO_2 emissions, GDP, trade openness, and FDI. As for the short-run scenarios, there is a unidirectional causality going from GDP to CO_2, and from FDI to CO_2. Interestingly, there is a bidirectional causality between trade openness and CO_2.

an environmental policy to be implemented on polluting industries under imperfect competition.[3] The authors focus on international competition or cooperation in setting environmental taxes by home and foreign counties and find that cooperative taxes may be higher than non-cooperative taxes depending on the magnitude of the equity stake. Unlike the authors' focus on environmental regulation within the international context, we analyze domestic competition in choosing policy options between emission taxes and environmental standards.

Our analysis complements the recent study of Dong and Chang (2020), which examines two pollution control instruments, uniform taxes and absolute standards, when polluting firms engage in overlapping ownership arrangements. The authors, in their analysis, assume that two polluting firms produce a homogenous good. Our paper further introduces product differentiation into the analysis to investigate how differentiated products (substitutes or complements) and equity stakes in overlapping ownership arrangements (OOAs) affect strategic policy options between environmental taxes and standards. Furthermore, we extend our analysis to consider that the government jointly determines equity share and emission tax (or standard) to maximize social welfare. This extension of policy mix permits us to see the relationship between ownership regulation and environmental regulation under product differentiation.

We summarize the primary findings as follows. First, compared to the case without ownership, the optimal environmental tax rate and absolute standard are higher (lower) when the differentiated goods produced by polluting firms are complements (substitutes). Second, we show that both the emission tax and absolute standard policies are equally efficient in their effects on the polluting firms' output and abatement decisions, the quality of the environment, consumer surplus, and social welfare, irrespective of whether the differentiated products are complements or substitutes. Third, for the case in which the government sets an optimal mix of equity share and emission tax (or standard) to maximize social welfare, the socially desirable (or allowable) equity share may exceed 50% for polluting firms only when their differentiated products are complements. The socially optimal equity share does not exist when the products are substitutes. For complementary products, the optimal equity share increases as the degree of product complementarity decrease. This analysis demonstrates the critical determinants of the socially optimal extent of overlapping ownership in differentiated duopoly markets. Our results have welfare implications for the options of environmental regulation between emission taxes and absolute standards, when the partial ownership stake is exogenously given, or when the government determines the socially optimal mix of equity share and emission tax (or standard). In analyzing the government's endogenous determination of an optimal

[3] Interesting cases of bilateral ownership arrangements as mentioned in Bárcena-Ruiz and Campo (2012) include the automobile industry. The Renault as a French auto firm has engaged in ownership arrangements with the Nissan (a Japanese auto manufacturer). Bárcena-Ruiz and Campo (2012) indicate that Renault acquires a 44.3% equity stake in Nissan Motor and Nissan Motor acquires a 15% stake in Renault. See Flath (1992), Fanti (2013, 2016), and Lopez and Vives (2019) for more discussions on examples of bilateral ownership arrangements.

equity share, we show that the equivalence of efficiency in implementing taxes and standards continues to hold.

The rest of the paper is organized as follows. Section 2 presents a model of product differentiation with overlapping ownership to analyze strategic environmental regulation. We examine two pollution control tools: emission taxes and absolute standards. For each policy, we analyze how OOAs affect the environment and social welfare. Section 3 investigates the case that the government optimally sets equity share and emission tax (or absolute standard). Section 4 summarizes the primary findings and their welfare implications. Section 5 concludes.

2 A differentiated duopoly model of strategic environmental regulation when polluting firms engage in overlapping ownership

We consider a duopolistic market with two polluting firms producing differentiated goods (1 and 2), and a competitive numeraire sector. Denote q_i as the quantity of good i produced by firm i, where $i = 1, 2$. The two firms engage in overlapping ownership arrangements therein each firm acquires equity on a share $\alpha(> 0)$ of its competitor's stocks or profits. We assume away corporate control in that neither firm has the power to determine its rival's output. As in the standard business operations, the equity share α is strictly less than 1/2.

The duopolistic firms generate pollutant emissions that damage the environment. For analytical simplicity without loss of generality, we assume that each firm's production technology is such that one unit of output generates one unit of pollutant emission. However, each firm can reduce pollution by investing in a costly abatement technique characterized by a quadratic function ka_i^2, where a_i is the abatement level of firm i and $k(> 0)$ is the abatement's cost-effectiveness. Firm i's emission level is then given as $e_i = q_i - a_i$ for $i = 1, 2$.

On the demand side of the differentiated duopoly market, we follow Singh and Vives (1984) and assume that the utility function of the representative consumer is:

$$U = A(q_1 + q_2) - \gamma q_1 q_2 - \frac{1}{2}(q_1^2 + q_2^2) + m,$$

$A(> 0)$ represents market size, m is the quantity of the numeraire good consumed, and γ stands for the degree of product differentiation. Note that $0 < \gamma < 1$ if the two products are substitutes and $-1 < \gamma < 0$ if they are complements. This utility specification generates a two-equation system with linear demands: $p_i = A - q_i - \gamma q_j$ for $i, j = 1, 2$ and $i \neq j$. The corresponding consumer surplus is: $CS = (q_i^2 + 2\gamma q_i q_j + q_j^2)/2$.

Unlike the homogeneous-good model of Dong and Chang (2020), the present study analyzes the choice of environmental policy and an optimal level of emission tax (standard) when polluting firms produce differentiated goods (either substitutes or complements). The government aims to maximize social welfare by implementing an environmental policy to control pollution in the differentiated duopoly with polluting firms damaging the environment. The first option is an emission tax policy whereby each firm pays a specific tax, denoted t, for each unit of pollutant emitted. The government's total revenue from the emission tax is:

$$T = t[(q_i - a_i) + (q_j - a_j)].$$

The second option is an emission standard policy whereby the government imposes a regulation limiting the amount of pollutants that firms can emit. Denoting the absolute standard by s, the level of abatement by firm i is then given as $a_i = q_i - s$.

Under the emission tax policy, firm $i's$ profit is:

$$\pi_i = pq_i - t(q_i - a_i) - k(a_i)^2. \tag{1}$$

Under the emission standard policy, firm $i's$ profit is:

$$\pi_i = pq_i - k(q_i - s)^2. \tag{2}$$

Given that each firm holds an equity share α in its rival's profit under OOAs,[4] the two firms' objective functions, denoted as $\{\prod_1, \prod_2\}$, for making their optimal output and abatement decisions are given, respectively, as

$$\Pi_1 = (1-\alpha)\pi_1 + \alpha\pi_2 \text{ and } \Pi_2 = (1-\alpha)\pi_2 + \alpha\pi_1, \tag{3}$$

π_i $(i = 1, 2)$ is firm $i's$ operating profits in (1) if the policy option is an emission tax or (2) if the policy option is an emission standard.

Given that the two firms engage in partial ownership, the producer surplus is:

$$PS = \prod_1 + \prod_2 = \pi_1 + \pi_2. \tag{4}$$

The environmental damage caused by the polluting emission is assumed to be quadratic:

$$ED = \lambda(e_1 + e_2)^2, \tag{5}$$

where λ represents the extent to which the environment deteriorates due to pollutant emissions.

Following the economics literature, social welfare is taken as the sum of the consumer surplus, producer surplus, and government revenues from the emission tax net the environmental damage. That is, the social welfare equation is:

$$\text{SW} = \text{CS} + \text{PS} + T - \text{ED}, \tag{6}$$

where $T = 0$ when the environmental policy is an emission standard.

[4] Analyzing the case of symmetric Cournot duopoly, Reitman (1994) shows that both competing firms have incentives to acquire a passive stake in each other's profits. Farrell and Shapiro (1990) note that there exists a mutually beneficial price at which each firm can sell some of its stock to its competitor if and only if the two firms' joint profits rise with the equity share (p. 287).

We consider a two-stage game structure to analyze how product differentiation affects environmental policy decisions when polluting firms engage in OOAs. At stage one, the government decides whether to impose a tax emission policy or an emission standard policy. At stage two, the firms compete *à la* Cournot by simultaneously determining their output and abatement levels that maximize individual profits. We solve the two-stage game by backward induction to obtain a subgame-perfect Nash equilibrium. For comparing with related studies and analytical simplicity, we follow Bárcena-Ruiz and Campo (2017) and Dong and Chang (2020) by assuming that $k = \lambda = 1/3$.

2.1 The emission tax policy under product differentiation

We begin our analysis with the policy option in which the government imposes an emission tax on polluting firms, 1 and 2. In the second stage, the firms compete in selling differentiated products and determining their abatement levels. By substituting the firms' profits from (1) into their objective functions in (3), we solve for the first-order conditions (FOCs). These FOCs imply that the optimal levels of output and abatement are given, respectively, as follows:

$$q_1^T = q_2^T = \frac{(1-\alpha)(A-t)}{\gamma + 2(1-\alpha)} \text{ and } a_1^T = a_2^T = \frac{3}{2}t, \tag{7}$$

T" stands for the emission tax policy. It follows from (7) that, other things being equal, each firm's output decreases with the emission tax, i.e., $\frac{\partial q_i^T}{\partial t} < 0$. We also see that an increase in the equity share provides a stronger incentive for the firms to lower their outputs, implying the output-reducing effect associated with overlapping ownership. That is, $\frac{\partial q_i^T}{\partial e} < 0$. It comes as no surprise that each firm's abatement increases when the emission tax is higher, i.e., $\frac{\partial a_i^T}{\partial t} > 0$.

In the first stage, the government solves for an optimal emission tax that maximizes social welfare as given in (6). To find the solution, we plug the results from (7) back into (1) and (3)–(6) to calculate the welfare function. The FOC for the government in pursuing welfare maximization implies that the optimal emission tax is:

$$t = \frac{2A(1-\alpha)[13 - 13\alpha + \gamma(6 - 3\alpha)]}{H}, \tag{8}$$

where $H \equiv (170 - 340\alpha + 138\gamma + 170\alpha^2 + 27\gamma^2 - 144\alpha\gamma + 6\alpha^2\gamma)$.

It can be verified from (8) that (i) $\frac{\partial t}{\partial \alpha} < 0$ for $\gamma > 0$ and (ii) $\frac{\partial t}{\partial \gamma} < 0$. The negative sign of the first derivative indicates that an increase in the equity share causes the optimal emission tax to decline when the differentiated products are substitutes. The negative sign of the second derivative suggests that the optimal emission tax is lower when the degree of product differentiation is higher. These results imply that when two polluting firms engage in OOAs, the changes in the optimal emission tax depend on the degree of product differentiation.

To calculate the reduced-form solutions, we plug t from (8) back into (1) and (3)–(6). This exercise yields:

Lemma 1 *For the case in which the welfare-maximizing government imposes an optimal emission tax on polluting firms that engage in OOAs, the equilibrium results are:*

$$a_1^T = a_2^T = \frac{3(26A - 52A\alpha + 12A\gamma + 26A\alpha^2 - 18A\alpha\gamma + 6A\alpha^2\gamma)}{2H},$$

$$q_1^T = q_2^T = \frac{9A(1-\alpha)(8-8\alpha+3\gamma)}{H},\ e_1^T = e_2^T = \frac{3A(1-\alpha)[11-11\alpha+\gamma(3+3\alpha)]}{H},$$

$$ED^T = \frac{12A^2(\alpha-1)^2[11-11\alpha+\gamma(3+3\alpha)]^2}{H^2},$$

$$CS^T = \frac{81A^2(1-\alpha)^2(1+\gamma)(8-8\alpha+3\gamma)^2}{H^2},$$

$$PS^T = \frac{\begin{array}{l}\{6A^2(1-\alpha)(\alpha^3(-9\gamma^2+1650\gamma-1897)-\alpha^2(1251\gamma^2+1848\gamma-5691)\\ +\alpha(243\gamma^3+981\gamma^2-1254\gamma-5691)+279\gamma^2+1452\gamma+1897\}\end{array}}{H^2},$$

$$SW^T = \frac{9A^2(1-\alpha)[11-11\alpha+\gamma(3+3\alpha)]}{H}. \tag{9}$$

Using Lemma 1, we can easily obtain the equilibrium values of the variables for the case without ownership by setting the equity share to zero ($\alpha = 0$). This permits us to conduct a comparison between the equilibrium outcomes under OOAs ($\alpha > 0$) and the equilibrium outcomes without ownership ($\alpha = 0$). We record the results (see details in Appendix A-1) as follows:

$$a_i^T(\alpha>0) - a_i^T(\alpha=0)\begin{cases} >0 & \text{when } \gamma<0 \\ <0 & \text{when } \gamma>0 \end{cases};\ q_i^T(\alpha>0) - q_i^T(\alpha=0)\begin{cases} >0 & \text{when } \gamma<0 \\ <0 & \text{when } \gamma>0 \end{cases};$$

$$e_i^T(\alpha>0) - e_i^T(\alpha=0)\begin{cases} >0 & \text{when } \gamma<0 \\ <0 & \text{when } \gamma>0 \end{cases};\ ED^T(\alpha>0) - ED^T(\alpha=0)\begin{cases} >0 & \text{when } \gamma<0 \\ <0 & \text{when } \gamma>0 \end{cases};$$

$$\pi_i^T(\alpha>0) - \pi_i^T(\alpha=0)\begin{cases} <0 & \text{when } \gamma<0 \\ >0 & \text{when } \gamma>0 \end{cases};$$

$$CS^T(\alpha > 0) - CS^T(\alpha = 0)\begin{cases} > 0 & \text{when } \gamma < 0 \\ < 0 & \text{when } \gamma > 0 \end{cases};$$

$$SW^T(\alpha > 0) - SW^T(\alpha = 0)\begin{cases} > 0 & \text{when } \gamma < 0 \\ < 0 & \text{when } \gamma > 0 \end{cases} \tag{10}$$

The above analysis leads to the following proposition:

Proposition 1 *When the government implements an optimal emission tax policy, for a duopolistic market with two polluting firms producing differentiated products and engaging in OOAs, the level of abatement, the quantity of output, the amount of pollutant emitted, the damage to the environment, consumer surplus, and social welfare are lower (higher) than the case without ownership when the differentiated products are substitutes (complements). In contrast, the firm's profit is higher (lower) than those without ownership when the differentiated products are substitutes (complements).*

2.2 The absolute standard policy under product differentiation

We now turn to the second policy option in which the government implements a uniform absolute emission standard for environmental regulation. In the first stage, the government sets an optimal emission standard to maximize social welfare. In the second stage, firms 1 and 2 simultaneously and independently make their output decisions that maximize respective objective functions in (3), where the operating profits are given in (2). We continue to use backward induction to obtain a subgame-perfect Nash equilibrium.

At stage two, the FOCs for the polluting firms imply that the optimal level of output is:

$$q_i^S = \frac{(1-\alpha)(3A+2s)}{3\gamma + 8(1-\alpha)}. \tag{11}$$

S" stands for the standard policy. We solve for the socially optimal level of emission standard by first substituting q_i^S from (11) back into (2)–(6) to calculate the social welfare function and then find the FOC for the government. This exercise yields:

$$s = \frac{(33 + 9\gamma - 9\alpha^2\gamma + 33\alpha^2 - 66\alpha)A}{H}, \tag{12}$$

where as defined earlier, $H \equiv (170 - 340\alpha + 138\gamma + 170\alpha^2 + 27\gamma^2 - 144\alpha\gamma + 6\alpha^2\gamma)$.

Equation (12) indicates that when the polluting firms engage in overlapping ownership and compete *à la* Cournot with product differentiation, the optimal emission standard is lower (i) when the value of equity share, α, is higher or (ii) when the degree of product differentiation, γ, is lower. That is, $\frac{\partial s}{\partial \alpha} < 0$ and $\frac{\partial s}{\partial \gamma} < 0$.

To calculate the reduced-form solutions, we plug the optimal emission standard s from (12) back into (2)–(6). This yields:

Lemma 2 *For the case in which the government imposes an optimal emission standard on polluting firms that engage in OOAs, the equilibrium values of the relevant variables are:*

$$q_1^S = q_2^S = \frac{9A(1-\alpha)[3\gamma + 8(1-\alpha)]}{H},$$

$$a_1^S = a_2^S = \frac{3A(1-\alpha)[3\gamma(2-\alpha) + 13(1-\alpha)]}{H},$$

$$ED^S = \left(\frac{16(33A + 9A\gamma - 9A\alpha^2\gamma + 33A\alpha^2 - 66A\alpha)}{9H}\right)^2,$$

$$\pi_1^S = \frac{\begin{array}{c}3A^2(1-\alpha)(\alpha^3(9\gamma^2 + 1662\gamma - 2183) - \alpha^2(1287\gamma^2 + 1662\gamma - 6549)\\ + \alpha(243\gamma^3 + 963\gamma^2 - 1662\gamma - 6549) + 315\gamma^2 + 1662\gamma + 2183\end{array}}{H^2},$$

$$CS^S = \frac{81A^2(1-\alpha)^2(1+\gamma)(8 - 8\alpha + 3\gamma)^2}{H^2},$$

$$SW^S = \frac{9A^2(1-\alpha)[11 - 11\alpha + \gamma(3 + 3\alpha)]}{H}. \tag{13}$$

By setting the equity share to zero, ($\alpha = 0$), we obtain the equilibrium values of the variables for the case without ownership. We then compare the equilibrium outcomes under OOAs ($\alpha > 0$), and those in the absence of ownership ($\alpha = 0$). This comparison depends crucially on whether the products are substitutes or complements (see details in Appendix A-2). The analysis leads to the following results:

$$a_i^S(\alpha > 0) - a_i^S(\alpha = 0)\begin{cases} > 0 & \text{when } \gamma < 0 \\ < 0 & \text{when } \gamma > 0 \end{cases};\ q_i^S(\alpha > 0) - q_i^S(\alpha = 0)\begin{cases} > 0 & \text{when } \gamma < 0 \\ < 0 & \text{when } \gamma > 0 \end{cases};$$

$$e_i^S(\alpha > 0) - e_i^S(\alpha = 0)\begin{cases} > 0 & \text{when } \gamma < 0 \\ < 0 & \text{when } \gamma > 0 \end{cases};\ ED^S(\alpha > 0) - ED^S(\alpha = 0)\begin{cases} > 0 & \text{when } \gamma < 0 \\ < 0 & \text{when } \gamma > 0 \end{cases};$$

$$\pi_i^S(\alpha > 0) - \pi_i^S(\alpha = 0)\begin{cases} > 0 & \text{when } \gamma < 0 \\ > 0 & \text{when } \gamma > 0 \end{cases},$$

$$CS^S(\alpha > 0) - CS^S(\alpha = 0)\begin{cases} > 0 & \text{when } \gamma < 0 \\ < 0 & \text{when } \gamma > 0 \end{cases},$$

$$SW^S(\alpha > 0) - SW^S(\alpha = 0)\begin{cases} > 0 & \text{when } \gamma < 0 \\ < 0 & \text{when } \gamma > 0 \end{cases} \tag{14}$$

Based on the equilibrium results in (13) and (14), we have the following proposition:

Proposition 2 *When the government implements an optimal emission standard policy, for a duopolistic market with two polluting firms producing differentiated products and engaging in OOAs, the level of abatement, the quantity of output, the amount of pollutant emitted, the damage to the environment, consumer surplus, and social welfare are lower (higher) than the case without ownership when the differentiated products are substitutes (complements). However, the firm's profit is higher than those without ownership, whether the differentiated products are substitutes or complements.*

2.3 Comparing the two alternative environmental policies

We proceed to evaluate and compare the two environmental policy instruments. The results in Eqs. (9) and (13) permit us to establish the following proposition:

Proposition 3 *When polluting firms engage in OOAs and compete in Cournot fashion under product differentiation, the emission tax and standard policies are equally efficacious in affecting the firms' production and emission decisions, the quality of the environment, consumer surplus, and social welfare.*

3 Socially optimal equity share and strategic environmental regulation

In the previous sections, we consider that the partial ownership stake is exogenously given. This section extends the analyses to the case in which the government endogenously sets equity share for ownership regulation to maximize social welfare. This extension permits us to see how the endogeneity of equity share under product differentiation affects the environment and social welfare, on the one hand, and how equity share regulation affects policy options between an emission tax and an emission standard, on the other.

We continue to use a two-stage game. In the first stage, the government determines an optimal equity share for ownership regulation and an optimal emission tax (or emission standard) for pollution control. In the second stage, taking the equity share and emission tax (or emission standard) as given, the two firms compete in making output and abatement decisions to maximize their respective objective functions.

We first focus on an emission tax policy. Backward induction implies that the polluting firms' optimal output and abatement levels are the same as those shown in (7) in the second stage. We then substitute (7) back into (1) and (3)–(5) to compute the social welfare function. Moving to the first stage, the government solves the optimal equity share and emission tax, $\{\alpha, t\}$, to maximize the social welfare function. The FOCs are:

$$\frac{\partial SW}{\partial \alpha} = 0 \text{ and } \frac{\partial SW}{\partial t} = 0,$$

which imply that the optimal values of equity share and emission tax are:

$$\tilde{\alpha} = \frac{1}{1-\gamma} \text{ and } \tilde{t} = \frac{4A}{9\gamma + 13}. \quad (15)$$

Equation (15) indicates that the socially optimal equity share depends on the degree of product differentiation. When the two products are complements, $(-1 < \gamma < 0)$, the optimal equity share exists and is given by $\tilde{\alpha} = 1/(1-\gamma)$. The higher (lower) the degree of product complementarity ($\gamma \to -1$), the lower (higher) the socially desirable equity share. These results imply that the optimal equity share may exceed 50% for OOAs firms producing two complements and is inversely related to the degree of product complementarity. As for the optimal emission tax, it increases as the degree of product differentiation is higher. When the two products are substitutes, $(0 < \gamma < 1)$, the optimal equity share does not exist. This result suggests that equity share cannot exceed 50% for polluting firms that produce two substitutable goods.

To calculate the reduced-form solutions, we substitute the results in (15) back into (7). We summarize the equilibrium values of the relevant variables in the following lemma:

Lemma 3 *When the government optimally determines equity share and emission tax to maximize social welfare, the equilibrium results for the case of two complements under the emission tax policy are:*

$$\tilde{q}_1^T = \tilde{q}_2^T = \frac{9A}{9\gamma + 13}, \ \tilde{a}_1^T = \tilde{a}_2^T = \frac{6A}{(9\gamma + 13)}, \ \tilde{e}_1^T = \tilde{e}_2^T = \frac{3A}{9\gamma + 13}$$

$$\widetilde{ED}^T = \frac{12A^2}{(9\gamma + 13)^2}, \ \tilde{\pi}_1^T = \tilde{\pi}_2^T = \frac{12A^2}{(9\gamma + 13)^2},$$

$$\widetilde{CS}^T = \frac{81A^2(\gamma + 1)}{(9\gamma + 13)^2}, \ \widetilde{SW}^T = \frac{9A^2}{9\gamma + 13}. \quad (16)$$

Switching to the other environmental policy, we examine the case where the government optimally sets the optimal equity share and emission standard, $\{\alpha, s\}$, to maximize social welfare. We substitute (7) back into (2)–(5) to compute the social welfare function, noting that $T = 0$ in (5). The FOCs are: $\frac{\partial SW}{\partial \alpha} = 0$ and $\frac{\partial SW}{\partial s} = 0$, which imply that the optimal values of equity share and emission standard are:

$$\tilde{\alpha}^S = \frac{1}{1-\gamma} \text{ and } \tilde{s} = \frac{3A}{9\gamma + 13} \tag{17}$$

To calculate the reduced-form solutions, we substitute the results in (17) back into (7). We summarize the equilibrium values of the relevant variables in the following lemma:

Lemma 4 *When the government optimally determines equity share and emission standard to maximize social welfare, the equilibrium results for two complements under the emission standard policy are:*

$$\tilde{q}_1^S = \tilde{q}_2^S = \frac{9A}{9\gamma + 13},\ \tilde{a}_1^S = \tilde{a}_2^S = \frac{6A}{9\gamma + 13},\ \tilde{e}_1^S = \tilde{e}_2^S = \frac{3A}{9\gamma + 13},$$

$$\widetilde{ED}^S = \frac{12A^2}{(9\gamma + 13)^2},\ \tilde{\pi}_1^S = \tilde{\pi}_2^S = \frac{24A^2}{(9\gamma + 13)^2},$$

$$\widetilde{CS}^S = \frac{81A^2(\gamma + 1)}{(9\gamma + 13)^2},\ \widetilde{SW}^S = \frac{9A^2}{9\gamma + 13}. \tag{18}$$

A comparison between Lemmas 3 and 4 reveals the following:

Proposition 4 *The socially optimal equity share is exactly identical, regardless of whether the government imposes an optimal emission tax or an optimal emission standard. Despite that firm profits are higher under the emission standard policy than under the emission tax policy, the two pollution control instruments are equivalent in terms of their effects on the environmental quality, consumer surplus, and social welfare. That is,*

$$\tilde{q}^T = \tilde{q}^S,\ \tilde{\pi}^T < \tilde{\pi}^S,\ \widetilde{ED}^T = \widetilde{ED}^S,$$

$$\widetilde{CS}^T = \widetilde{CS}^S, \text{ and } \widetilde{SW}^T = \widetilde{SW}^S.$$

4 Welfare implications under differentiated oligopoly with ownership

This section summarizes the welfare implications of our model results for strategic environmental policy (an emission tax or an absolute standard) in a differentiated duopoly with overlapping ownership arrangements.

For the case of an emission tax policy, as shown in Proposition 1, if the products of two polluting firms are imperfectly substitutable, overlapping ownership arrangements (OOAs) between the polluting firms cause their output levels to decline. Such an output-reducing effect translates to lower polluting emissions and environmental damage. The anti-competitive nature of OOAs increases the prices of the differentiated products and the two firms' profits, causing consumer surplus to go down. Furthermore, the decrease in social welfare is due to the negative impact of OOAs consumer surplus dominating the positive impact on the firms' profits and the environmental damage.

In contrast, for the case in which two polluting firms' products are complements, OOAs between the firms cause their output levels to *increase*. This output-raising effect translates to higher polluting emissions and more severe environmental damage. The cooperative nature of OOAs reduces the prices of the complements, which increases consumer surplus, lowers the firms' profits, and increases social welfare.

For the case of an absolute standard policy, as shown in Proposition 2, when two polluting firms engage in OOAs, the changes in market outcomes, environmental quality, and social welfare depend crucially on the nature of the differentiated products. OOAs anti-competitively lower the firms' output levels in the case of two substitutes, and such an output-reducing effect translates to lower polluting emissions and mild environmental damage. The anti-competitive nature of OOAs increases the product prices, raises the firms' profits, lowers the consumer surplus, and reduces social welfare.

In contrast, for the case in which differentiated products are complements, OOAs act as a facilitator in increasing the polluting firms' output level, raising polluting emissions and leading to more severe environmental damage. The cooperative nature of OOAs reduces the products' price, increases consumer surplus, firms' profits and social welfare,

We compare differences or similarities between the two pollution control instruments. As shown in Proposition 3, product differentiation does not affect the economic equivalence between the emission taxes and absolute standards in pollution control.

Furthermore, we have shown in Proposition 4 that when the government endogenously sets an optimal mix of equity share and an environmental policy (either an emission tax or standard), the two policies are equivalent in their effects on the environmental quality, consumer surplus, and social welfare. It should be noted that, for the two pollution control instruments, the profits of the polluting firms are relatively lower under the emission tax policy. The firms' profits under the tax policy plus the total emission tax revenues collected by the government are equal to the two firms' profits under the standard policy. An alternative way of explaining the differences in firms' profits under both environmental policies is to look at the results when the government changes its policy from an optimal standard to an optimal tax. Under the standard policy, there involves transferring a portion of producer surplus to the government's tax revenue.

5 Concluding remarks

The strategic use of a policy instrument may help improve the quality of the environment by reducing environmental damage resulting from pollution or waste. This paper examines how product differentiation and overlapping ownership affect the policy options between an emission tax and an emission standard for environmental regulation. We present a duopolistic competition model in which two polluting firms that produce differentiated products may engage in OOAs. Compared to the benchmark case without ownership, and under the emission tax option, we show that the environmental damage, the tax emission, the quantities of differentiated products, consumer surplus, and social welfare increase (decrease) when the two products are complements (substitutes). Second, when the polluting firms engage in OOAs, under the absolute standard policy, the optimal output, consumer surplus, welfare, environmental damage, and emission standard are lower when the two products are substitutes. Conversely, when the two products are complements, the optimal output, environmental damage, and welfare are higher. Furthermore, we compare the equilibrium outcomes between the two alternative policy tools—emission taxes and standards. The two policies are equally efficient in affecting the firms' output and abatement decisions, emissions, environmental quality, consumer surplus, and social welfare.

Finally, we examine an optimal policy combination of equity share and an environmental policy (either an emission tax or standard) endogenously chosen by the government. When two differentiated products are substitutes, there does not exist a socially optimal equity share. However, when the products are complements, a socially optimal equity share exceeds 50% for firms engaging in OOAs. The endogenous determination of equity share for OOA firms selling complimentary products does not affect policy options between emission taxes and environmental standards since they are equally efficacious in pollution control.

Appendix A

A-1. Comparison between the equilibrium outcomes under OOAs ($\alpha > 0$) and those in the absence of ownership ($\alpha = 0$). The case of tax emission policy

$$
\begin{aligned}
t^T(\alpha > 0) - t^T(\alpha = 0) = {} & \frac{2A(1-\alpha)(-13\alpha + 6\gamma - 3\alpha\gamma + 13)}{-340\alpha + 138\gamma + 170\alpha^2 + 27\gamma^2 - 144\alpha\gamma + 6\alpha^2\gamma + 170} \\
& - \frac{2A(6\gamma + 13)}{27\gamma^2 + 138\gamma + 170}
\end{aligned}
$$

$$
= -\frac{18A\alpha\gamma(120\gamma - 134\alpha + 27\gamma^2 - 81\alpha\gamma - 9\alpha\gamma^2 + 134)}{(27\gamma^2 + 138\gamma + 170)(6\alpha^2\gamma + 170\alpha^2 - 144\alpha\gamma - 340\alpha + 27\gamma^2 + 138\gamma + 170)}.
$$

It follows that $t^T(\alpha > 0) - t^T(\alpha = 0) > 0$ when $\gamma < 0$.

$$q^T(\alpha > 0) - q^T(\alpha = 0) = \frac{9(1-\alpha)[8(1-\alpha)+3\gamma]A}{-340\alpha + 138\gamma + 170\alpha^2 + 27\gamma^2 - 144\alpha\gamma + 6\alpha^2\gamma + 170} - \frac{9A(3\gamma+8)}{(27\gamma^2 + 138\gamma + 170)}$$

$$= -\frac{\gamma 27 A\alpha(138\gamma - 182\alpha + 27\gamma^2 - 66\alpha\gamma + 182)}{(27\gamma^2 + 138\gamma + 170)(6\alpha^2\gamma + 170\alpha^2 - 144\alpha\gamma - 340\alpha + 27\gamma^2 + 138\gamma + 170)}.$$

We thus have $(\alpha > 0) - q^T(\alpha = 0) > 0$ when $\gamma < 0$.

$$e^T(\alpha > 0) - e^T(\alpha = 0) = \frac{3A(1-\alpha)(-11\alpha + 3\gamma + 3\alpha\gamma + 11)}{-340\alpha + 138\gamma + 170\alpha^2 + 27\gamma^2 - 144\alpha\gamma + 6\alpha^2\gamma + 170} - \frac{3A(3\gamma+11)}{27\gamma^2 + 138\gamma + 170}$$

$$= -\frac{\gamma 81 A\alpha(6\gamma - 16\alpha + 5\alpha\gamma + 3\alpha\gamma^2 + 16)}{(27\gamma^2 + 138\gamma + 170)(6\alpha^2\gamma + 170\alpha^2 - 144\alpha\gamma - 340\alpha + 27\gamma^2 + 138\gamma + 170)}.$$

It follows that $e^T(\alpha > 0) - e^T(\alpha = 0) > 0$ when $\gamma < 0$.

$$a_1^T(\alpha > 0) - a_1^T(\alpha = 0) = \frac{3(26A - 52A\alpha + 12A\gamma + 26A\alpha^2 - 18A\alpha\gamma + 6A\alpha^2\gamma)}{2(-340\alpha + 138\gamma + 170\alpha^2 + 27\gamma^2 - 144\alpha\gamma + 6\alpha^2\gamma + 170)} - \frac{78A + 36A\gamma}{54\gamma^2 - 276\gamma + 340}$$

$$= -\frac{27A\alpha\gamma(120\gamma - 134\alpha + 27\gamma^2 - 81\alpha\gamma - 9\alpha\gamma^2 + 134)}{(27\gamma^2 + 138\gamma + 170)(6\alpha^2\gamma + 170\alpha^2 - 144\alpha\gamma - 340\alpha + 27\gamma^2 + 138\gamma + 170)}.$$

This result implies that $a_1^T(\alpha > 0) - a_1^T(\alpha = 0) > 0$ when $\gamma < 0$.

$$ED^T(\alpha > 0) - ED^T(\alpha = 0) = \frac{12A^2(1-\alpha)^2(-11\alpha + 3\gamma + 3\alpha\gamma + 11)^2}{(-340\alpha + 138\gamma + 170\alpha^2 + 27\gamma^2 - 144\alpha\gamma + 6\alpha^2\gamma + 170)^2} - \frac{12A^2(3\gamma+11)^2}{(27\gamma^2 + 138\gamma + 170)^2}.$$

It follows that $ED^T(\alpha > 0) - ED^T(\alpha = 0) > 0$ when $\gamma < 0$.

$$CS^T(\alpha > 0) - CS^T(\alpha = 0) = \frac{81A^2(1-\alpha)^2(1+\gamma)(8 - 8\alpha + 3\gamma)^2}{(-340\alpha + 138\gamma + 170\alpha^2 + 27\gamma^2 - 144\alpha\gamma + 6\alpha^2\gamma + 170)^2} - \frac{81A^2(1+\gamma)(3\gamma+8)^2}{(138\gamma + 27\gamma^2 + 170)^2}$$

It follows that $CS^T(\alpha > 0) - CS^T(\alpha = 0) > 0$ when $\gamma < 0$.

$$\pi_i^T(\alpha > 0) - \pi_i^T(\alpha = 0)$$
$$= \left(\frac{\begin{array}{l} 3A^2(1-\alpha)(-9\alpha^3\gamma^2 + 1650\alpha^3\gamma - 1897\alpha^3 - 1251\alpha^2\gamma^2 \\ -1848\alpha^2\gamma + 5691\alpha^2 + 243\alpha\gamma^3 + 981\alpha\gamma^2 - 1254\alpha\gamma \\ -5691\alpha + 279\gamma^2 + 1452\gamma + 1897) \end{array}}{(6\alpha^2\gamma + 170\alpha^2 - 144\alpha\gamma - 340\alpha + 27\gamma^2 + 138\gamma + 170)^2} \right) - \frac{3A^2(1452\gamma + 279\gamma^2 + 1897)}{(138\gamma + 27\gamma^2 + 170)^2}$$

$$= \frac{27A^2\alpha\gamma \left(\begin{array}{l} 729\alpha^3\gamma^5 - 126\,198\alpha^3\gamma^4 - 1185\,435\alpha^3\gamma^3 - 3625\,812\alpha^3\gamma^2 - 3856\,716\alpha^3\gamma \\ -501\,160\alpha^3 + 100\,602\alpha^2\gamma^5 + 1311\,714\alpha^2\gamma^4 + 6230\,196\alpha^2\gamma^3 + 13\,084\,848\alpha^2\gamma^2 \\ +10\,933\,416\alpha^2\gamma + 1503\,480\alpha^2 - 19\,683\alpha\gamma^6 - 381\,996\alpha\gamma^5 - 2668\,302\alpha\gamma^4 \\ -8867\,286\alpha\gamma^3 - 14\,570\,136\alpha\gamma^2 - 10\,296\,684\alpha\gamma - 1503\,480\alpha + 19\,683\gamma^6 \\ +258\,066\gamma^5 + 1365\,174\gamma^4 + 3668\,868\gamma^3 + 5111\,100\gamma^2 + 3219\,984\gamma + 501\,160 \end{array} \right)}{(27\gamma^2 + 138\gamma + 170)^2(6\alpha^2\gamma + 170\alpha^2 - 144\alpha\gamma - 340\alpha + 27\gamma^2 + 138\gamma + 170)^2}$$

We thus have $\pi^T(\alpha > 0) - \pi^T(\alpha = 0) > 0$ when $\gamma < 0$.

$$SW^T(\alpha > 0) - SW^T(\alpha = 0)$$
$$= \frac{9A^2(1-\alpha)(-11\alpha + 3\gamma + 3\alpha\gamma + 11)}{(-340\alpha + 138\gamma + 170\alpha^2 + 27\gamma^2 - 144\alpha\gamma + 6\alpha^2\gamma + 170)} - \frac{9A^2(3\gamma + 11)}{27\gamma^2 + 138\gamma + 170}$$

$$= -\frac{\gamma 243A^2\alpha\left(-16\alpha + 6\gamma + 5\alpha\gamma + 3\alpha\gamma^2 + 16\right)}{\left(138\gamma + 27\gamma^2 + 170\right)\left(-340\alpha + 138\gamma + 170\alpha^2 + 27\gamma^2 - 144\alpha\gamma + 6\alpha^2\gamma + 170\right)}$$

It follows that $SW^T(\alpha > 0) - SW^T(\alpha = 0) > 0$ when $\gamma < 0$.

A-2. Comparison between the equilibrium outcomes under OOAs ($\alpha > 0$) and those in the absence of ownership ($\alpha = 0$). The case of emission standard policy

$$s^s(\alpha > 0) - s^s(\alpha = 0)$$
$$= \frac{33A - 66A\alpha + 9A\gamma + 33A\alpha^2 - 9A\alpha^2\gamma}{-340\alpha + 138\gamma + 170\alpha^2 + 27\gamma^2 - 144\alpha\gamma + 6\alpha^2\gamma + 170} - \frac{33A + 9A\gamma}{27\gamma^2 + 138\gamma + 170}$$

$$= -\frac{81A\alpha\gamma(6\gamma - 16\alpha + 5\alpha\gamma + 3\alpha\gamma^2 + 16)}{(27\gamma^2 + 138\gamma + 170)(6\alpha^2\gamma + 170\alpha^2 - 144\alpha\gamma - 340\alpha + 27\gamma^2 + 138\gamma + 170)}$$

This result implies that $s^s(\alpha > 0.5) - s^s(\alpha = 0) > 0$ when $\gamma < 0$.

$$q^s(\alpha > 0) - q^s(\alpha = 0)$$
$$= \frac{-9A(\alpha - 1)(3\gamma - 8\alpha + 8)}{6\alpha^2\gamma + 170\alpha^2 - 144\alpha\gamma - 340\alpha + 27\gamma^2 + 138\gamma + 170} - \frac{72A + 27A\gamma}{27\gamma^2 + 138\gamma + 170}$$

$$= -\frac{27A\alpha\gamma(138\gamma - 182\alpha + 27\gamma^2 - 66\alpha\gamma + 182)}{(27\gamma^2 + 138\gamma + 170)(6\alpha^2\gamma + 170\alpha^2 - 144\alpha\gamma - 340\alpha + 27\gamma^2 + 138\gamma + 170)}$$

It follows that $q^s(\alpha > 0) - q^s(\alpha = 0) > 0$ when $\gamma < 0$.

$$\pi_1^s(\alpha > 0) - \pi_1^s(\alpha = 0)$$

$$= 3A^2 \frac{\begin{array}{l}(1-\alpha)(9\alpha^3\gamma^2 + 1662\alpha^3\gamma - 2183\alpha^3 - 1287\alpha^2\gamma^2 \\ -1662\alpha^2\gamma + 6549\alpha^2 + 243\alpha\gamma^3 + 963\alpha\gamma^2 \\ -1662\alpha\gamma - 6549\alpha + 315\gamma^2 + 1662\gamma + 2183)\end{array}}{(6\alpha^2\gamma + 170\alpha^2 - 144\alpha\gamma - 340\alpha + 27\gamma^2 + 138\gamma + 170)^2} - \frac{3A^2(315\gamma^2 + 1662\gamma + 2183)}{(27\gamma^2 + 138\gamma + 170)^2}.$$

$$\pi_i^s(\alpha > 0) - \pi_i^s(\alpha = 0)$$

$$= \frac{\begin{array}{l}81A^2\alpha\gamma(-243\alpha^3\gamma^5 - 47\,358\alpha^3\gamma^4 - 409\,599\alpha^3\gamma^3 - 1176\,492\alpha^3\gamma^2 - 1081\,508\alpha^3\gamma \\ +70\,720\alpha^3 + 34\,992\alpha^2\gamma^5 + 447\,444\alpha^2\gamma^4 + 2056\,572\alpha^2\gamma^3 + 4041\,984\alpha^2\gamma^2 + 2789\,008\alpha^2\gamma \\ -212\,160\alpha^2 - 6561\alpha\gamma^6 - 127\,818\alpha\gamma^5 - 878\,796\alpha\gamma^4 - 2808\,918\alpha\gamma^3 - 4238\,280\alpha\gamma^2 - 2333\,492\alpha\gamma \\ +212\,160\alpha + 6561\gamma^6 + 84\,564\gamma^5 + 433\,836\gamma^4 + 1103\,004\gamma^3 + 1372\,788\gamma^2 + 625\,992\gamma - 70\,720\end{array}}{(27\gamma^2 + 138\gamma + 170)^2(6\alpha^2\gamma + 170\alpha^2 - 144\alpha\gamma - 340\alpha + 27\gamma^2 + 138\gamma + 170)^2}$$

A numerical simulation shows that $\pi_i^s(\alpha > 0) - \pi_i^s(\alpha = 0) > 0$ for any $-1 < \gamma < 1$.

$$a_1^s(\alpha > 0) - a_1^s(\alpha = 0)$$

$$= \frac{3A(1-\alpha)(6\gamma - 13\alpha - 3\alpha\gamma + 13)}{6\alpha^2\gamma + 170\alpha^2 - 144\alpha\gamma - 340\alpha + 27\gamma^2 + 138\gamma + 170} - \frac{3A(6\gamma + 13)}{27\gamma^2 + 138\gamma + 170}$$

$$= -\frac{\gamma 27A\alpha(120\gamma - 134\alpha + 27\gamma^2 - 81\alpha\gamma - 9\alpha\gamma^2 + 134)}{27\gamma^2 + 138\gamma + 170(6\alpha^2\gamma + 170\alpha^2 - 144\alpha\gamma - 340\alpha + 27\gamma^2 + 138\gamma + 170)}.$$

This result implies that $a_1^s(\alpha > 0) - a_1^s(\alpha = 0) > 0$ when $\gamma < 0$.

$$ED^s(\alpha > 0) - ED^s(\alpha = 0)$$

$$= \frac{4}{3}\left(\frac{33A - 66A\alpha + 9A\gamma + 33A\alpha^2 - 9A\alpha^2\gamma}{-340\alpha + 138\gamma + 170\alpha^2 + 27\gamma^2 - 144\alpha\gamma + 6\alpha^2\gamma + 170}\right)^2 - \frac{12(11A + 3A\gamma)^2}{\left(27\gamma^2 + 138\gamma + 170\right)^2}$$

It follows that $ED^s(\alpha > 0) - ED^s(\alpha = 0) > 0$ when $\gamma < 0$.

$$CS^s(\alpha > 0) - CS^s(\alpha = 0)$$

$$= (\gamma + 1)\left(\frac{-9A(\alpha - 1)(3\gamma - 8\alpha + 8)}{6\alpha^2\gamma + 170\alpha^2 - 144\alpha\gamma - 340\alpha + 27\gamma^2 + 138\gamma + 170}\right)^2 - \frac{81A^2(3\gamma + 8)^2(\gamma + 1)}{(138\gamma + 27\gamma^2 + 170)^2}$$

$$= -\frac{243A^2\alpha\gamma(\gamma+1)\begin{pmatrix} -15\,444\alpha^3\gamma^3 - 152\,280\alpha^3\gamma^2 - 482\,004\alpha^3\gamma - 495\,040\alpha^3 + 11\,664\alpha^2\gamma^4 \\ +176\,256\alpha^2\gamma^3 + 900\,720\alpha^2\gamma^2 + 1926\,864\alpha^2\gamma + 1485\,120\alpha^2 - 2187\alpha\gamma^5 \\ -56\,376\alpha\gamma^4 - 435\,780\alpha\gamma^3 - 1496\,664\alpha\gamma^2 - 2407\,716\alpha\gamma - 1485\,120\alpha \\ +4374\gamma^5 + 56\,376\gamma^4 + 290\,520\gamma^3 + 748\,224\gamma^2 + 962\,856\gamma + 495\,040 \end{pmatrix}}{(27\gamma^2+138\gamma+170)^2(6\alpha^2\gamma+170\alpha^2-144\alpha\gamma-340\alpha+27\gamma^2+138\gamma+170)^2}.$$

It follows that $CS^s(\alpha > 0) - CS^s(\alpha = 0) > 0$ when $\gamma < 0$.

$$SW^s(\alpha > 0) - SW^s(\alpha = 0)$$
$$= \frac{9A^2(1-\alpha)(3\gamma - 11\alpha + 3\alpha\gamma + 11)}{6\alpha^2\gamma + 170\alpha^2 - 144\alpha\gamma - 340\alpha + 27\gamma^2 + 138\gamma + 170} - \frac{9A^2(3\gamma+11)}{27\gamma^2 + 138\gamma + 170}$$

$$= -\frac{\gamma 243A^2\alpha(6\gamma - 16\alpha + 5\alpha\gamma + 3\alpha\gamma^2 + 16)}{(27\gamma^2+138\gamma+170)(6\alpha^2\gamma+170\alpha^2-144\alpha\gamma-340\alpha+27\gamma^2+138\gamma+170)}$$

We thus have the result that $SW^s(\alpha > 0) - SW^s(\alpha = 0) > 0$ when $\gamma < 0$.

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