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Abstract

This paper investigates firm incentives for developing environmentally clean technologies in a simple two-country model with international oligopoly, and compares them under price and quantity regulations with and without policy cooperation between governments. Under any policy regime, whether firm incentives are either excessive or insufficient from a welfare point of view depends on the marginal environmental damage and the degree of emission spillovers. If the marginal damage is relatively large, a quantity instrument encourages innovation more than a price instrument. In addition, under either regime of price and quantity regulations, policy cooperation (harmonization) necessarily enhances welfare in each country, but it does not necessarily increase firms' innovation incentives.

Keywords Technology innovation; International oligopoly ; Environmental policy; Policy harmonization

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1 Introduction

It is widely believed that some form of international policy coordination is necessary to tackle global environmental problems such as global warming.[1] Economists have long argued that when each country non-cooperatively sets the domestic environmental regulations, outcomes may be inefficient because of externalities through transboundary pollution and/or imperfectly competitive international markets (Barrett 1994; Kennedy 1994). Thus economists emphasize the need for cooperative policies such as international environmental agreements (IEA) to internalize the externalities and to achieve the efficient outcome.

Economists also recognize that promoting development of cleaner technologies is important for overcoming environmental problems:[2] they have focused attention on incentives of firms in developing cleaner technologies and analyzed the effectiveness of different policy instruments in inducing environmental innovation (Downing and White 1986; Milliman and Primce 1989; Fischer et al. 2003). Most previous studies show that incentive-based environmental policies are superior to command-and-control policies towards fostering innovation for developing cleaner technologies.

However, to the best of author's knowledge, there is no study investigating the relationship between different environmental policies with and without the cooperation of governments and firm incentives in developing cleaner technologies in open-economy settings. This relationship is important because international firms that invest strategically in environmental R&D make decisions according to, whether national governments determine policies cooperatively or non-cooperatively and according to what policy instruments each government chooses. Thus, previous studies leave important issues unanswered: What policy instruments (price or quantity regulation) in international environmental agreements most encourage signatories' innovation in cleaner technologies? Are firms' strategic incentives for environmental R&D either excessive or insufficient from the viewpoint of each country's welfare? How would policy cooperation among countries affect firms' incentives to innovate?

To address these issues, we construct a simple two-country model of international oligopoly and transboundary pollution and investigate and compare firms' strategic incentives for developing cleaner technology under four international policy regimes: (i) each country non-cooperatively (or unilaterally) sets the level of tax regulations on its domestic polluting firm, (ii) each country non-cooperatively sets the level of quantity regulations (iii) countries cooperatively set the level of a harmonized tax, and (iv) countries cooperatively set the level of harmonized quantity regulations. In our model, the governments are assumed to be unable to credibly commit to the level of environmental regulations. This lack of regulatory commitment gives incentives to firms to influence the level of regulations through their environmental R&D activities.

Within the above framework, we first investigate whether firm incentives are excessive or

[1]For this point, Stern Review (Stern (2007)) indicates that "stronger, more coordinated action is required to stabilise concentrations of greenhouse gases in the atmosphere."

[2]For example, Kneese and Schultze (1975) argued that "over the long haul, perhaps the most important single criterion on which to judge environmental policies is the extent they spur new technology towards the efficient conservation of environmental quality."

insufficient from the perspective of domestic welfare. The lack of regulatory commitment induces firms to strategically over- or under-invest in any regime because the innovation affects the domestic and foreign regulations, depending on the magnitude of marginal environmental damages and the degree of emission spillovers. We show that if the marginal environmental damages are large, the firm incentives are insufficient under non-cooperative tax regulations but are excessive under non-cooperative and cooperative quantity regulations.

Second, we compare firm incentives under different policy regimes. We show that, in either case, with or without policy cooperation, firm incentives under quantity regulations are greater than those under price regulations if the marginal damages are greater. This result is important because previous studies using a closed-economy model conclude that incentive-based regulations are superior to command-and-control regulations for inducing the firms to invest in clean technology.

Finally, we compare firm incentives with and without cooperation between governments. Although stringent regulation under policy cooperation (harmonization) increases the value of and need for innovation, firms do not necessarily have greater incentives under cooperative regimes than non-cooperative regimes. This is because under non-cooperative policy regimes, firms also have strategic incentives to relax domestic regulations and to tighten foreign regulations when investing in environmental R&D. In contrast, if the policy is set cooperatively and harmonized between nations, such strategic aspects of innovations are absent. Whether the policy instrument is price or quantity regulations, our results demonstrate that firm incentives are greater under non-cooperative regimes than under cooperative regimes if the marginal damages are large.

As mentioned above, firms have strategic incentives to change their environmental investment in order to affect future regulations if the governments cannot commit themselves to environmental policies. The lack of regulatory commitment is a key assumption in our study, and we believe it is justified by numerous examples of firms acting in this manner.[3] For example, DuPont's successful R&D efforts to find substitutes for chlorofluorocarbons (CFCs) changed the stringency of Montreal Protocol.[4] Another example of firms making strategic investment choices (or voluntary approaches) is the Keidanren Voluntary Action Plan on the Environment (Keidanren 1997) to promote efforts to curb CO_2 emissions, which is a unilateral initiative of Japan's most influential business association. It was established even before the adoption of the Kyoto Protocol's in 1997. Furthermore, the target the Japanese government accepted under the Kyoto Protocol was partly based on consultations with Keidanren. Other examples include actions by German industry groups when a coalition of Social Democrats and the Green Party proposed an energy tax in 1999 (Conrad 2001). These examples show how firms recognize a strategic incentive to act in ways that

[3] Kolstad (2000, p.211) indicates that "[c]ertainly, it seems reasonable to argue that levels of R&D investments are more difficult to change than taxes and so these are set in the first stage because environmental regulators are rarely willing and able to commit." Tarui and Polasky (2005) indicate that large firms (e.g., large automobile companies, electric power generators, or oil companies) who producing a significant share of emissions may have an incentive to alter investment strategically in order to induce favorable shifts in future environmental policy. See Requate and Unold (2003) and Requate (2005a) for the comparison of innovation incentives under different timing and commitment regimes of environmental policies in a closed-economy model. In addition, the lack of credibility in environmental policy makings also appears in Conrad (2001), Glazer and Janeba (2004), Poyago-Theotoky (2007), and Puller (2006).

[4] See Tarui and Polasky (2005) and Puller (2006) on this point.

might influence future regulation.

This paper relates to the literature on the effects of different environmental policies on technological innovation in a closed economy setting (Downing and White 1986; Milliman and Prince 1989; Denicolo 1999; Fischer et al. 2003). Previous studies generally show that incentive-based environmental policies are more likely to foster cost-effective technology innovation and diffusion, than policies based on command-and-control approaches.[5] Those studies and ours differ in that they use a single-government model with perfectly competitive firms producing dirty goods, whereas we use a two-country model with international oligopoly.[6]

This paper also relates to the literature on the strategic environmental policy in an open-economy model (Conrad 1993; Barrett 1994; Kennedy 1994; Ulph 1996), which closely follows the strategic trade literature pioneered by Brander and Spencer (1985). Dealing with issues of strategic trade in the output market and transboundary pollution, they demonstrate considerable strategic relationships among governments for environmental policymaking, and government incentives to impose inefficiently less (or more) stringent environmental regulations.[7] Since they focus on strategic interactions between governments, they do not investigate firms' incentives for environmental R&D. The paper most related to ours is Conrad (2001), which considers policy regimes with different timings of environmental policymaking (setting taxes and standards) in the model of strategic environmental policy. He shows that if the industry anticipates that taxes and fees will be introduced in upcoming years, it seems rational to act in advance in order to mitigate the necessity for taxes. While his study focuses on investigating firms' strategic incentives to adjust output and abatement before regulations are introduced, ours investigates and *compares* the strategic R&D incentives of firms under several policy regimes.[8]

The structure of this paper is as follows. In Section 2 we present the elements of the model. In Section 3 we analyze firm incentives for environmental R&D under non-cooperative tax and quantity regulations, and then we compare them. In Section 4 we analyze the same under cooperative policy regimes. In section 5 we analyze the effect of policy cooperation on firms' innovation incentives. Section 6 offers concluding remarks.

[5]For a detailed survey of the influence of different environmental policies on innovation and diffusion, see Jaffe et al. (2002) and Requate (2005b).

[6]Some studies compare R&D incentives in a single-government model with an imperfectly competitive market (Montero 2002; Glazer and Janeba 2004; Puller 2006; Poyago-Theotoky 2007). Glazer and Janeba (2004) show that if the government is unable to commit the level of regulations, the firm has an incentive to overinvest in reducing emissions under price regulation, but an incentive to underinvest under quantity regulation.

[7]For general discussion and analysis of this subject, see also Rauscher (1997).

[8]Recently, Ulph and Ulph (2007) investigate environmental R&D of international oligopolistic firms in the model of strategic environmental policymaking. They consider the case where governments have two policy instruments (an emissions tax and an R&D subsidy) and can commit to the policies before firms choose their R&D investment. Our study differs from theirs in that we explicitly compare the firm incentives under price and quantity regulations with and without policy cooperation between governments. In addition, we consider the case where governments are unable to commit to the regulation level credibly.

2 The Model

Consider two exporting firms 1 and 2 located in two different countries 1 and 2, respectively. Each firm $i \in \{1,2\}$ produces homogenous goods and engages in Cournot (quantity) competition in a world market. In the production process, firms generate emissions that are proportional to output. Firm i's emissions harm, not only country i's welfare, but also country j's welfare partly, i.e., its emissions are transboundary. In order to reduce emissions, regulation policies are implemented. We examine four regimes with respect to policymaking in two countries: (i) regime NT refers to the non-cooperative tax regulation where each government non-cooperatively sets domestic emission tax rates; (ii) regime NQ refers to the non-cooperative quantity regulation where each government non-cooperatively sets the level of domestic emissions; (iii) regime CT refers to the cooperative tax regulation where governments set cooperative(harmonized) tax rates; (iv) regime CQ refers to cooperative quantity regulation where governments set cooperative (harmonized) level of emissions.

The timing of the game is as follows. In period 1, each government sets a policy: under NT (NQ), it sets a domestic tax (the level of domestic emissions) non-cooperatively; under CT (CQ), it sets a harmonized tax (the harmonized level of emissions) cooperatively. In period 2, given the regulation policies, each firm non-cooperatively decides outputs. We investigate the firm incentives for environmental R&D that are evaluated in period 0, i.e., R&D incentives that we examine have strategic natures because they take into account the effect of own environmental R&D on the domestic and foreign policies or cooperative policy as well as on own and rival firm's behavior. The assumption that R&D decisions are made before regulators set policies is particularly valid when R&D is typically a long-term activity and a government or regulator is unable to commit to the level of environmental policy credibly.[9]

We define firm incentives for environmental R&D (in period 0) as the marginal profit of an improvement in the firm's emission technologies. In other words, the firm incentives are equivalent to its willingness to pay for a marginal improvement in emission technologies.[10] Throughout the analysis, we also define and investigate government incentives to promote environmental R&D. Although R&D efforts are undertaken by firms, it is significant to consider the government incentives and to compare them with firm incentives, as described later.

2.1 The Firms

In period 2, firms 1 and 2 engage in Cournot competition in a world market. The emissions by firm i is $a_i = e_i y_i$, where e_i is the emission coefficient and y_i is the output of firm i. Profits of firm

[9]Notice that the governments are assumed to be unable to commit to the *level* of the policy, but to be able to commit to the *type* of the policy and the *presence or absence* of policy cooperation between governments.

[10]It seems that the definition of firm incentives would be too simplified, but in fact, this simplification enables us to clearly compare the firm incentives under different policy regimes without numerical simulations.

i ($i = \{1,2\}$, $i \neq j$) are defined by

$$\pi_i = \begin{cases} p(y_i + y_j)\, y_i - t_i\, e_i\, y_i & \text{under regime NT} \\ p\left(\dfrac{a_i}{e_i} + \dfrac{a_j}{e_j}\right)\dfrac{a_i}{e_i} & \text{under regime NQ} \\ p(y_i + y_j)\, y_i - \bar{t}\, e_i\, y_i & \text{under regime CT} \\ p\left(\dfrac{\bar{a}}{e_i} + \dfrac{\bar{a}}{e_j}\right)\dfrac{\bar{a}}{e_i} & \text{under regime CQ} \end{cases} \tag{1}$$

where $p(\cdot)$ is the inverse demand of goods in a world market, t_i and a_i are the emission tax rate and the level of emissions in country i that are non-cooperatively set by government i, and $\bar{t}$ and $\bar{a}$ are harmonized policies that cooperatively set by both governments. For simplicity, we assume that marginal production costs of both firms are zero.[11] The inverse demand function is assumed to be $p(y_1 + y_2) = 1 - y_1 - y_2$. Each firm's incentives for environmental R&D denoted by FI_i are evaluated by the value of $-\partial\pi_i/\partial e_i$ in period 0, i.e., the marginal profit of a decrease in emission coefficient.

2.2 The Governments

Welfare of country i ($i = \{1,2\}$, $i \neq j$) is defined by the sum of the profits of the domestic firm, the tax revenues (if any), and the environmental damages from emissions:

$$W_i = \begin{cases} \pi_i + t_i e_i y_i - d_i(e_i y_i + \gamma e_j y_j) & \text{under regime NT,} \\ \pi_i - d_i(a_i + \gamma a_j) & \text{under regime NQ,} \\ \pi_i + \bar{t} e_i y_i - d_i(e_i y_i + \gamma e_j y_j) & \text{under regime CT,} \\ \pi_i - d_i(\bar{a} + \gamma \bar{a}) & \text{under regime CQ,} \end{cases} \tag{2}$$

where d_i is the constant marginal environmental damage (MED) from emissions and $\gamma \in [0,1]$ is the degree of emission spillovers. Domestic consumption in each country is sufficiently small in comparison with world consumption, so that each government ignores the effect of its policies on domestic consumers, and any tax payment is purely distributional. Incentives for environmental R&D of government i (GI_i) are evaluated by the value of $-\partial W_i/\partial e_i$ in period 0, i.e., the marginal welfare gain of a decrease in emission coefficient of firm i.

It is important to derive government incentives and to compare them with firm incentives. Suppose temporarily that firm i's investment costs for attaining a marginal improvement in emission technologies are Δ_i as a whole. If $FI_i > GI_i$ and $FI_i > \Delta_i > GI_i$ hold in equilibrium, then firm i undertakes the investment that reduces the domestic welfare. Thus, if $FI_i > GI_i$ holds in equilibrium, we say firm incentives are *excessive*. On the other hand, if $FI_i < GI_i$ and $FI_i < \Delta_i < GI_i$ hold in equilibrium, then firm i does not invest while the investment, if done, increases the domestic welfare. Thus, if $FI_i < GI_i$ holds in equilibrium, then the firm incentives are said to be *insufficient*. In both cases, the firm does not have right incentives for environmental R&D, and thus government intervention in R&D may be justified.

[11] The results obtained in this paper are also qualitatively valid for constant marginal cost of production.

3 Under Non-cooperative Policy Regimes

3.1 Emission Taxes (Regime NT)

The model is solved backwards. In period 2, firm i maximizes (1) taking y_j, t_i, and t_j as given. The first-order conditions of the problem are $y_i = (1 - e_i t_i - y_j)/2$ for $i \neq j$, which is the best-response function of firm i. Then the equilibrium output in period 2 is $y_i = (1 - 2e_i t_i + e_j t_j)/3$.

In period 1, each country non-cooperatively chooses the emission tax rate so as to maximize the domestic welfare (2). The first-order conditions of the problem are $t_i = (6e_i d_i - 3\gamma e_j d_i - e_j t_j - 1)/4e_i$ for $i = 1,2$ $i \neq j$. We obtain the equilibrium tax in period 1 as follows:

$$t_i^{NT} = \frac{e_i(8d_i + \gamma d_j) - 2e_j(d_j + 2\gamma d_i) - 1}{5e_i} \qquad \forall i = 1,2, \tag{3}$$

where superscript NT represents the variable in the equilibrium of regime NT.[12] The effects of the marginal improvements (marginal decreases) in emission technology on the own and other's equilibrium tax rates are obtained by

$$-\frac{\partial t_i^{NT}}{\partial e_i} = -\frac{1 + 2e_j(d_j + 2\gamma d_i)}{5e_i^2} < 0, \quad -\frac{\partial t_j^{NT}}{\partial e_i} = \frac{2(d_i + 2\gamma d_j)}{5e_j} > 0. \tag{4}$$

Lemma 1
A marginal innovation in domestic firm lowers the domestic tax and raises the foreign tax rate.

Substituting (3) into the equilibrium output in period 2 and evaluating it at symmetric equilibrium, we obtain the equilibrium outputs of each firm as $y^{NT} = \{2 - ed(2-\gamma)\}/5$, where variables without subscript indicate those in symmetric equilibrium. Thus, we need to assume $d < \frac{2}{(2-\gamma)e}$ for ensuring $y^{NT} > 0$ in equilibrium.

Assumption NT: $d < \frac{2}{(2-\gamma)e}$ holds in NT equilibrium.

Next we investigate firm i's incentives for environmental R&D. The firm incentives are defined as the marginal profits of improvement in its own emission technologies, that is, $FI_i^{NT} \equiv -\partial \pi_i^{NT}/\partial e_i$. Deriving FI_i^{NT} and then evaluating it at a symmetric equilibrium, we have

$$FI^{NT} = \frac{4d(3+\gamma)\{2 - ed(2-\gamma)\}}{25} > 0, \tag{5}$$

which indicates that each firm's innovation incentive is always positive and is increasing in γ.[13] Government i's incentives are defined as the marginal welfare gain of the improvement in emission technologies of domestic firm, that is, $GI_i^{NT} \equiv -\partial W_i^{NT}/\partial e_i$. Evaluating it at a symmetric equilibrium, we have

$$GI^{NT} = \frac{d\{4(3+\gamma) + ed(4+3\gamma)(4\gamma - 3)\}}{25} > 0, \tag{6}$$

[12] We allow for the possibility of $t^{NT} < 0$ in equilibrium. In other words, each government may have incentives for subsidizing the domestic emissions (or exports).

[13] The sign condition can be obtained by using Assumption NT.

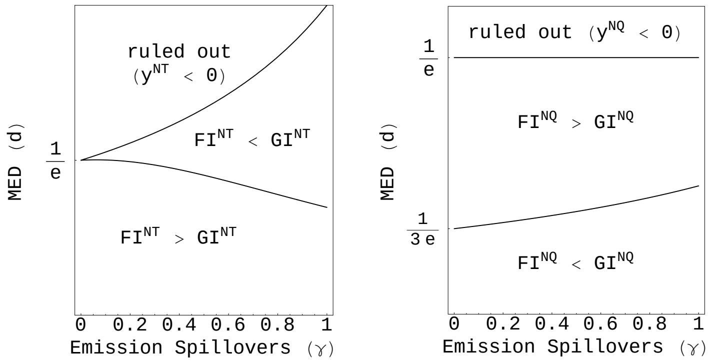

Figure 1: Firm and government incentives under regimes NT (left) and NQ (right).

which is also positive and increasing in γ.

Note that from (4) we find that innovations relax (tighten) the domestic (foreign) tax more when the value of γ becomes larger. Thus, both FI^{NT} and GI^{NT} are increasing in γ.

Comparing (5) and (6), we obtain the following proposition.

Proposition 1

Under regime NT, firm incentives for environmental R&D are insufficient (excessive) if MED and/or the emission spillovers are larger (smaller). Formally,

$$FI^{NT} \lesseqqgtr GI^{NT} \Leftrightarrow d \gtreqqless \frac{4(3+\gamma)}{(12+3\gamma+8\gamma^2)e}.$$

Proof: See Appendix.

The differences between FI^{NT} and GI^{NT} are the effects of innovations on environmental damages and tax revenues. Domestic innovations increase (decrease) domestic emissions for large (small) value of d, whereas they necessarily decrease foreign emissions.[14] When d and γ are relatively small, the domestic innovations reduce tax revenues and the benefits from emission reductions in domestic and foreign countries are small. Thus, $FI^{NT} > GI^{NT}$ holds for smaller d and γ. When d and γ are large, the domestic innovations increase tax revenues and the benefits from emission reductions in foreign country become large.[15] Thus, $FI^{NT} < GI^{NT}$ holds for larger d and γ.

The left panel of Fig.1 illustrates the result in (γ, d) plane. From Assumption NT, the region above $d = 2/\{(2-\gamma)e\}$ curve is ruled out. The critical value of d shown in Proposition 1 separates the remaining regions into $FI^{NT} > GI^{NT}$ region and $FI^{NT} < GI^{NT}$ region. In $FI^{NT} > GI^{NT}$ region, the private innovation incentives are excessive in the sense that the private gains from innovation exceed the domestic welfare gains form innovation. Thus, in this case, the firm may undertake

[14]They can be confirmed by $-\partial(e_i y_i^{NT})/\partial e_i = -\{2-ed(8+\gamma)\}/5$ and $-\partial(e_j y_j^{NT})/\partial e_i = -ed(4+3\gamma)/5 < 0$.

[15]Notice that, when d is large, the domestic emissions are increased by innovations. However, the net domestic gains, which are defined by $(t_i^{NT} - d_i)e_i y_i^{NT}$, are increased by innovations for large d.

welfare-reducing R&D. In $FI^{NT} < GI^{NT}$ region, on the contrary, the private innovation incentives are insufficient, and the firm may not undertake welfare-enhancing R&D.

3.2 Quantity Regulations (Regime NQ)

Next, consider non-cooperative regulation by quantity, which is defined as setting of the total allowable volume of emissions a_i by each government. Because e_1, e_2, a_1, and a_2 are determined in period 0 and 1, we need not to consider the firms output choices in period 2 as long as the quantity regulation is binding.

The welfare maximization problems of government i ($i = 1,2$) in period 1 is

$$\max_{a_i} \; p\left(\frac{a_i}{e_i} + \frac{a_j}{e_j}\right)\frac{a_i}{e_i} - d_i(a_i + \gamma a_j).$$

Solving the first-order conditions of both governments, we obtain the equilibrium level of emissions (quantity regulations) in country i as $a_i^{NQ} = e_i(1 - 2e_i d_i + e_j d_j)/3$, where superscript NQ represents the variable under NQ regime. Then we have

$$-\frac{\partial a_i^{NQ}}{\partial e_i} = -\frac{1 - 4e_i d_i + e_j d_j}{3} \gtreqless 0, \quad -\frac{\partial a_j^{NQ}}{\partial e_i} = -\frac{e_j d_i}{3} < 0. \tag{7}$$

Lemma 2
A marginal innovation in domestic firm relaxes or tightens the domestic quantity regulation and tightens the foreign quantity regulation.

In contrast to the tax case, a marginal innovation tightens the domestic and foreign quantity regulation when d_i is small. The intuition is as follows. When d_i is small, the regulator i sets a larger domestic emission allowance. In this case, a marginal innovation greatly increases domestic outputs, which makes the regulator strengthen the quantity regulation.[16]

Using the equilibrium level of emissions, we obtain the outputs of each firm in symmetric equilibrium as $y^{NQ} = (1 - ed)/3$. Thus, we need to assume the following so that y^{NQ} be positive.

Assumption NQ: $d < \frac{1}{e}$ holds in NQ equilibrium.

We then derive the firm and government incentives for environmental R&D under NQ regime. Deriving $FI_i^{NQ} \equiv -\partial \pi_i^{NQ}/\partial e_i$ and then evaluating it at a symmetric equilibrium, we have

$$FI^{NQ} = \frac{d(1 + 5ed)}{9} > 0, \tag{8}$$

which is always positive although an innovation may tighten the domestic regulation (as shown in Lemma 2). This is because the innovation necessarily tightens the foreign regulation, which dominates the effect on domestic regulation.[17]

[16] Notice that as in a closed-economy model of Puller (2006), higher innovation causes the regulator to tighten the regulation in the case of the uniform standard whereas it causes the regulator to decrease the tax in the case of an emission tax. These properties are partly carried on into our open economy model.

[17] Since the equilibrium level of quantity regulation is independent of γ, FI^{NQ} is also independent of γ. Notice that this is due to the linearity of environmental damage function we assume.

The government incentives are also defined by $GI_i^{NQ} \equiv -\partial W_i^{NQ}/\partial e_i$, and, in a symmetric equilibrium, it can be obtained by

$$GI^{NQ} = \frac{d\{4+ed(3\gamma-4)\}}{9} > 0, \tag{9}$$

which is always positive and increasing in γ.

Comparing (8) and (9), we have the following proposition:

Proposition 2

Under regime NQ, firm incentives for environmental R&D are insufficient (excessive) if MED is smaller (larger) and/or the emission spillovers are larger (smaller). Formally,

$$FI^{NQ} \lesseqgtr GI^{NQ} \Leftrightarrow d \lesseqgtr \frac{1}{(3-\gamma)e}$$

Proof: Immediate from (8) and (9).

In contrast to Proposition 1, the smaller the MED, the more likely firm incentives are smaller than government incentives. This result is straightforward. The difference between FI^{NQ} and GI^{NQ} is the effect of innovation on environmental damages. As shown in Lemma 2, when d is small, innovations decrease both countries' emissions. Thus, government incentives are larger than firm incentives for smaller values of d. On the other hand, when d is large, innovations increase net domestic emissions and therefore the reverse holds. The right panel of Fig.1 illustrates the results.

3.3 Comparison between Regimes NT and NQ

Next we compare NT and NQ equilibrium in two points: welfare and innovation incentives of firms. The welfare in each equilibrium can be obtained, respectively, by

$$W^{NT} = \frac{\{2-ed(2-\gamma)\}\{1-ed(1+7\gamma)\}}{25}, \quad W^{NQ} = \frac{(1-ed)\{1-ed(1+3\gamma)\}}{9}.$$

We then state:

Proposition 3

Welfare in each country is higher under regime NQ compared to regime NT. In addition, welfare differentials become larger as emission spillovers become greater. Formally, $W^{NQ} > W^{NT}$ and $d(W^{NQ} - W^{NT})/d\gamma > 0$.

Proof: The first assertion comes from $W^{NQ} - W^{NT} = 7\{1-ed(1-3\gamma)\}^2/225 > 0$, while the second one from $d(W^{NQ} - W^{NT})/d\gamma = 14ed\{1-ed(1-3\gamma)\}/75 > 0$.

The welfare advantage of regime NQ over regime NT can be confirmed by the fact that equilibrium outputs under NQ are smaller than those under NT.[18] Under NT, each government cannot help setting lower tax rates out of fear that setting higher tax rates induces foreign firm to produce more, while under NQ the foreign firm cannot change its output after the domestic

[18] In particular, we have $y^{NT} - y^{NQ} = \frac{1-ed(1-3\gamma)}{15} > 0$ with using Assumption NQ.

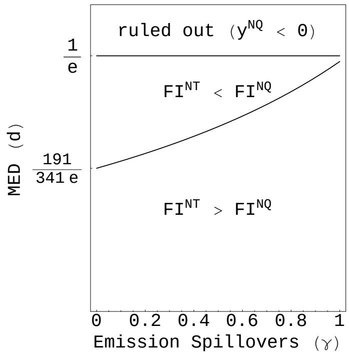

Figure 2: Firm incentives for environmental R&D: Non-cooperative price vs. quantity Regulations

government sets policy. Thus, the noncooperative tax becomes inefficiently lower and the welfare differentials become larger as damages from foreign emissions become larger (i.e. γ is larger).[19]

We then compare the firm incentives under NT with those under NQ.

Proposition 4

Firm incentives for environmental R&D are larger under regime NT compared to regime NQ for small MED and/or large emission spillovers, and vice versa. Formally,

$$FI^{NT} \gtreqless FI^{NQ} \Leftrightarrow d \lesseqgtr \frac{191+72\gamma}{\{341-36\gamma(1+\gamma)\}e}.$$

Proof: From (5) and (8), we obtain the critical value of d displayed in the proposition. In addition, it is obvious that the critical value is increasing in γ.

Contrary to the widespread notion that incentive-based (price) regulations induce firms' innovation more than command-and-control (quantity) regulations, our result indicates that the relative ranking of firm incentives crucially depends on d and γ if we take into account an international oligopoly and lack of commitment power of regulators. The underlying intuition is as follows: When d is small, innovations tighten the domestic quantity regulation as well as the foreign quantity regulation as Lemma 2 shows. On the other hand, innovations relax the domestic tax regulation while tighten the foreign regulation. Thus, $FI^{NT} > FI^{NQ}$ holds for smaller d. When d is large, innovations relax the domestic regulation and tighten the foreign regulation under either regime. However, the regulation is more strict under NQ than NT (equivalently, $y^{NT} > y^{NQ}$), the benefits from increases in outputs are greater under NQ than NT. This is why $FI^{NT} < FI^{NQ}$ holds for larger d. In addition, from (4) and (7), the larger γ, the greater an innovation decreases (increases) the domestic (foreign) tax rates, while the effect of an innovation on the domestic and foreign quantity regulations is independent of γ. Thus, $FI^{NT} > FI^{NQ}$ holds for larger value of γ. Fig. 2 simply illustrates the results.

[19]It can be confirmed by the fact that t^{NT} is decreasing in γ but a^{NQ} is independent in γ.

4 Under Cooperative Policy Regimes

In this section, we examine the issue of international harmonization on pollution controls. Suppose an official multilateral agreement, for example an international climate agreement, requires a single and harmonization of environmental policies in each country, by which both countries are encouraged to abide. The principle is that both governments set harmonized regulations to maximize the sum of both countries' welfare. Firm incentives for environmental R&D investigated in this section are those in the case where firms expect such a policy harmonization to be implemented.

4.1 Emission Taxes (Regime CT)

In period 2, each firm chooses outputs so as to maximize its profits (1), given the rival's outputs and harmonized tax rate $\bar{t}$. Solving the first-order conditions of both firms characterizes the equilibrium outputs: $y_i = \{1-(2e_i-e_j)\bar{t}\}/3$.

In period 1, the collective choice on harmonized tax rate is decided so as to maximize the sum of both countries' welfare. The maximization problem is represented by $\max_{\bar{t}}\ W_1+W_2$. Arranging the first-order condition of the problem, we obtain the equilibrium tax rate t^{CT} as

$$t^{CT} = \Big\{\sum_{i}^{2} e_i + \sum_{i\neq j}^{2} 6e_i^2(d_i+\gamma d_j) - 3e_1e_2(d_1+d_2)(1+\gamma)\Big\}\Big/\{2(e_1+e_2)^2\},$$

where superscript CT represents the variable under regime CT.[20] Differentiating t^{CT} in $-e_i$ and evaluating it at a symmetric equilibrium, we obtain

$$-\frac{\partial t^{CT}}{\partial e_i} = \frac{1}{8e^2} > 0. \tag{10}$$

Lemma 3
A marginal innovation in one firm necessarily raises the harmonized tax rate.

As before, we assume the (symmetric) equilibrium outputs $y^{CT} = \{1-ed(1+\gamma)\}/4$ to be positive:

Assumption CT: $d < \frac{1}{(1+\gamma)e}$ holds in CT equilibrium.

We next derive firm and government incentives for environmental R&D in period 0. The firm incentive is defined by $FI_i^{CT} \equiv -\partial\pi_i^{CT}/\partial e_i$ as before. Evaluating at a symmetric equilibrium, it leads to

$$FI^{CT} = \frac{\{1-ed(1+\gamma)\}\{1+4ed(1+\gamma)\}}{16e} > 0. \tag{11}$$

Innovations raise the harmonized tax but lower the net marginal cost of own production (e_it^{CT}), and thus increase outputs and profits of the innovating firm.[21] This is why FI^{CT} is always

[20] The second-order condition of the problem is $-2(e_1+e_2)^2/9 < 0$.

[21] Actually, the effect of the domestic innovation on the domestic outputs is $-\partial y_i^{CT}/\partial e_i = \{1+4ed(1+\gamma)\}/8e > 0$, which is evaluated at a symmetric equilibrium.

positive. The government incentives defined by $GI_i^{CT} \equiv -\partial W_i^{CT}/\partial e_i$, evaluating at a symmetric equilibrium, lead to

$$GI^{CT} = \frac{1+ed(1+\gamma)\{6+ed(-7+9\gamma)\}}{16e} > 0. \tag{12}$$

Then we state:

Proposition 5

Under regime CT, firm incentives for environmental R&D are necessarily insufficient. In addition, the degree of insufficiency becomes larger as emission spillovers become greater. Formally, $FI^{CT} < GI^{CT}$ *and* $d(GI^{CT} - FI^{CT})/d\gamma > 0$.

Proof: From (11) and (12), we have $GI^{CT} - FI^{CT} = d(1+\gamma)\{3-ed(3-13\gamma)\}/16 > 0$, where the inequality comes from Assumption CT. In addition, the differentials are clearly increasing in γ.

Intuition is as follows. The domestic innovation increases both the domestic tax revenues and the environmental damages from the domestic pollution, but the net effect on domestic welfare is positive.[22] Thus, $FI^{CT} < GI^{CT}$ holds even if $\gamma = 0$. As a result, under the cooperative tax regime, the private innovation incentives are necessarily insufficient for a domestic welfare point of view, which is illustrated in the left panel of Fig.3.

4.2 Quantity Regulations (Regime CQ)

Next we derive the firm and government incentives for environmental R&D in the case where harmonized quantity regulation (emission allowance) is cooperatively decided. As before, each firm cannot produce outputs beyond the predetermined level $\bar{a}/e_i = y_i$. Thus, we need not to investigate the behavior of each firm in period 2 unless the quantity regulation is not binding.

The cooperative emission standard $\bar{a} = e_i y_i$ is chosen in period 1 so as to maximize joint welfare $W_1 + W_2$. The maximization problem is

$$\max_{\bar{a}} \sum_{i \neq j}^{2} \left\{ p\left(\frac{\bar{a}}{e_i} + \frac{\bar{a}}{e_j}\right)\frac{\bar{a}}{e_i} - d_i \bar{a}(1+\gamma) \right\}.$$

The first-order condition, after some manipulation, is [23]

$$\bar{a} = e_1 e_2 \Big[\sum_{i \neq j}^{2} \Big\{ e_i - e_i e_j d_i (1+\gamma) \Big\} \Big] / \{2(e_1+e_2)^2\}.$$

Differentiating this with respect to $-e_i$ and evaluating it at a symmetric equilibrium, we have

$$-\frac{\partial \bar{a}}{\partial e_i} = -\frac{1-2ed(1+\gamma)}{8} \gtreqless 0. \tag{13}$$

[22] This can be confirmed by

$$-\frac{\partial\{(t^{CT}-d_i)e_i y_i^{CT}\}}{\partial e_i} = \frac{d\{3+\gamma+3ed(-1+2\gamma+3\gamma^2)\}}{16} > 0,$$

where the inequality comes from Assumption CT.

[23] The second-order condition is $-\{2(e_1+e_2)^2\}/(e_1^2+e_2^2) < 0$.

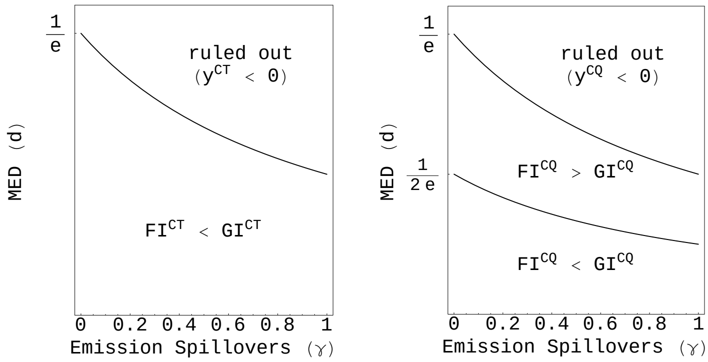

Figure 3: Firm and government incentives under regimes CT (left) and CQ (right).

Lemma 4
A marginal innovation in one firm tightens or relaxes the harmonized quantity regulation.

Notice also that (13) shows that when d is smaller (larger) than $1/\{2(1+\gamma)e\}$, then a marginal innovation decreases (increases) $\bar{a}$.

The next assumption ensures that the (symmetric) equilibrium outputs $y^{CQ} = \{1 - ed(1+\gamma)\}/4$ is positive:

Assumption CQ: $d < \frac{1}{(1+\gamma)e}$ holds in CQ equilibrium.

The firm incentives are defined by $FI_i^{CQ} \equiv -\partial \pi_i^{CQ}/\partial e_i$. Deriving it and then evaluating it at a symmetric equilibrium, we have

$$FI^{CQ} = \frac{1 + e^2 d^2 (1+\gamma)^2}{16e} > 0. \tag{14}$$

The government incentives are defined by $GI_i^{CQ} \equiv -\partial W_i^{CQ}/\partial e_i$. At a symmetric equilibrium, we have

$$GI^{CQ} = \frac{\{(1 - ed(1+\gamma)\}\{1 + 3ed(1+\gamma)\}}{16e} > 0. \tag{15}$$

Then we state:

Proposition 6
Under regime CQ, firm incentives for environmental R&D are insufficient (excessive) if MED and/or the emission spillovers are smaller (larger). Formally,

$$FI^{CQ} \gtreqless GI^{CQ} \;\Leftrightarrow\; d \gtreqless \frac{1}{2(1+\gamma)e}$$

Proof: Immediate from (14) and (15).

The result is straightforward: when the marginal innovation relaxes the quantity regulation (i.e., it increases $\bar{a}$), it increases the total emissions in one country as well. Thus, in this case, the government incentives are smaller than the firm incentives. Actually, the critical value of d in

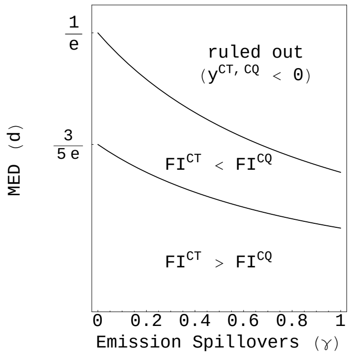

Figure 4: Firm incentives for environmental R&D: Cooperative price vs. quantity regulations

Proposition 6 coincides with that for $-\partial \bar{a}/\partial e_i = 0$. The result is illustrated in the right panel of Fig.3.

4.3 Comparing between Regimes CT and CQ

Let us now compare firm incentives in CT with those in CQ equilibrium. Obviously, the welfare under CT and that under CQ are same because $y^{CT} = y^{CQ}$.[24] In other words, if we do not consider innovative activities of firms, the two regimes (CT and CQ) are indifferent. However, the firm incentives for environmental R&D are different between under two regimes. Comparing (11) and (14) yields the following result.

Proposition 7
Firm incentives for environmental R&D are larger under regime CT compared to regime CQ for small MED and/or small emission spillovers, and vice versa. Formally,

$$FI^{CT} \gtreqless FI^{CQ} \Leftrightarrow d \lesseqgtr \frac{3}{5(1+\gamma)e} \tag{16}$$

Proof: Immediately from (11) and (14).

As under the non-cooperative policy regimes, the ranking with regard to firm incentives for environmental R&D crucially depends on d and γ. The underlying intuition is as follows. From (10) and (13), we find that for larger value of d, innovations relax the harmonized level of quantity regulations while they necessarily strengthen that of price (tax) regulations. Thus, $FI^{CT} < FI^{CQ}$ holds for larger value of d. On the other hand, when d is small, innovations tighten both cooperative policies. However, under CT, innovations reduce the net marginal cost of production ($e_i t^{CT}$) and thus increase outputs of the innovating firm (see footnote 21). This is why $FI^{CT} > FI^{CQ}$ holds for smaller value of d. Fig. 4 simply illustrates the result.

[24] In detail, we have $W^{CT} = W^{CS} = \{1 - ed(1+\gamma)\}^2/8$ in a symmetric equilibrium.

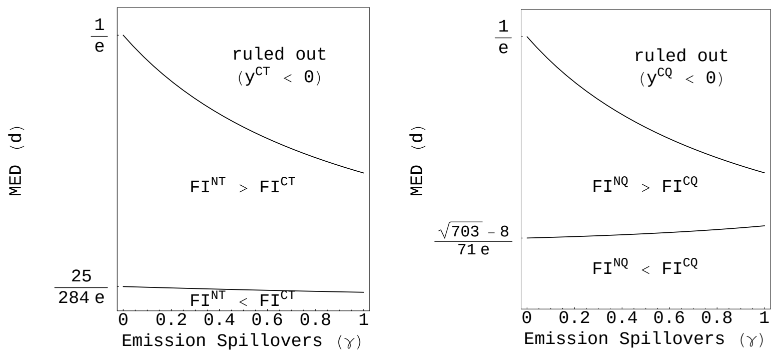

Figure 5: Non-cooperative vs. cooperative Regulations: Tax regulation (left) and quantity regulation (right)

5 Does Policy Cooperation Encourage Environmental Innovations?

In this section we compare firm incentives under non-cooperative policy regimes with those under cooperative policy regimes. It is obvious that the level of regulations is more strict and the welfare of both countries is greater under cooperative policies than under noncooperative policies (either tax or quantity regulations). However, rankings of firm incentives for environmental R&D are not easy to determine because more strict regulations under cooperative regimes increase the value and need of innovation for firms, while they also eliminate the strategic advantages of innovation of relaxing the domestic regulations and tightening the foreign regulations.

5.1 Non-cooperative vs. Cooperative Tax Regulations

The following proposition compares FI^{NT} with FI^{CT}.

Proposition 8

Firm incentives for environmental R&D are larger under regime NT compared to regime CT for large MED and/or large emission spillovers, and vice versa. Formally,

$$FI^{NT} \gtreqless FI^{CT} \;\Leftrightarrow\; d \gtreqless \Psi \equiv \frac{50}{\left\{309+53\gamma+\sqrt{(259)^2+3\gamma(19718+6403\gamma)}\right\}e},$$

where $0<\Psi<1/\{(1+\gamma)e\}$ *holds for all* $\gamma\in[0,1]$.

Proof: See Appendix.

As shown by the left panel of Fig. 5, firm incentives are larger under NT than under CT except when d is extremely small. Innovations under NT have the effect of lowering domestic taxes and raising foreign taxes, whereas those under CT have the effect of raising both countries' tax. Because of this strategic effect of innovation that widens the gap between domestic and foreign tax rates under NT, $FI^{NT} > FI^{CT}$ holds in most regions. However, as we see from (5) and (11), FI^{NT} converges to zero but FI^{CT} converges to $1/(16e)$ as d approaches to zero.[25] Thus, $FI^{NT} < FI^{CT}$ holds for extremely small d.

5.2 Quantity Regulation

Finally, we compare firm incentives under NQ with CQ.

Proposition 9
Firm incentives for environmental R&D are larger under regime NQ compared to regime CQ for large MED and/or small emission spillovers, and vice versa. Formally,

$$FI^{NQ} \gtreqless FI^{CQ} \Leftrightarrow d \gtreqless \Omega \equiv \frac{\sqrt{(19-9\gamma)(37+9\gamma)}-8}{e(71-9\gamma(2+\gamma))},$$

where $0 < \Omega < 1/\{(1+\gamma)e\}$ *holds for all* $\gamma \in [0,1]$.

Proof: See Appendix.

The right panel of Fig. 5 illustrates the results. When d is large, innovations relax the domestic regulations and tighten the foreign regulations under NQ, while they relax both countries' regulations under CQ. Thus, $FI^{NQ} > FI^{CQ}$ holds for relatively large d. On the other hand, when d is small, under both regimes, innovations tighten both countries' regulations. In this case, the level of regulations is more strict under CQ than under NQ, which means that a marginal profits of innovations are larger under CQ than under NQ. Thus, $FI^{NQ} < FI^{CQ}$ holds for relatively small d.

6 Concluding Remarks

Employing a simple two-country model of strategic environmental policy, we investigate and compare firm incentives for developing cleaner technology under several policy regimes: Non-cooperative policy settings of tax and quantity regulations (NT and NQ) and cooperative policy settings of tax and quantity regulations (CT and CQ).

The results obtained in this paper are summarized as follows: First, under any regime, firm incentives are either excessive or insufficient from a welfare point of view, depending on the marginal environmental damages and the degree of emission spillovers. This may provide rationales for government intervention in environmental R&D. Second, contrary to the general view, firm incentives are not necessarily greater under price regulations than under quantity regulations. Under both non-cooperative and cooperative regimes, firm incentives under quantity regulations are greater than those under price regulations if the environmental damages are large. This finding may be significant for designing international environmental agreements. Finally, under either regime of tax and quantity regulations, policy cooperation (harmonization) necessarily enhances

[25] This is because the equilibrium tax rate under NT becomes negative for extremely small d whereas that under CT are always positive.

welfare in each country, but does not necessarily increase firms' innovation incentives. In particular, if environmental damages are large, policy cooperation lowers firms' innovation incentives.

Appendix

Proof of Proposition 1: By (5) and (6), we have

$$FI^{NT} - GI^{NT} = \frac{d\{4(3+\gamma) - ed(12+3\gamma+8\gamma^2)\}}{25}.$$

Thus, we have $FI^{NT} \lesseqgtr GT^{NT} \Leftrightarrow d \gtreqless \frac{4(3+\gamma)}{(12+3\gamma+8\gamma^2)e}$. Differentiating of this critical value of d with respect to γ yields

$$\frac{d\left(\frac{4(3+\gamma)}{(12+3\gamma+8\gamma^2)e}\right)}{d\gamma} = \frac{4(3-48\gamma-8\gamma^2)}{e(12+3\gamma+8\gamma^2)} \gtreqless 0 \Leftrightarrow \gamma \lesseqgtr 0.062,$$

which implies that except for the case where emission spillovers are extremely small, the critical value of d becomes smaller as γ becomes larger. Thus, $FI^{NT} < GI^{NT}$ is more likely to hold when γ becomes large.

Proof of Proposition 8: From (5) and (11), we have

$$FI^{NT} - FI^{CT} = \eta d^2 + \kappa d + \mu, \tag{A.1}$$

where

$$\begin{aligned} \eta &= \frac{(-71+66\gamma+41\gamma^2)e}{100} \gtreqless 0 \Leftrightarrow \gamma \gtreqless \hat{\gamma} \equiv \frac{20\sqrt{10}-33}{41} \approx 0.738, \\ \kappa &= \frac{309+53\gamma}{400} > 0, \quad \mu = -\frac{1}{16e} < 0. \end{aligned}$$

In the case of $\gamma \geq \hat{\gamma}$ (i.e. $\eta \geq 0$), the condition for (A.1)> 0 is $d < d_S$ or $d > d_L$, where d_S and d_L are the smaller and the larger solution for (A.1)$= 0$. d_S and d_L are derived as follows:

$$\begin{aligned} d_S &= \frac{50}{e(309+53\gamma - \sqrt{(259)^2+3\gamma(19718+6403\gamma)}}, \\ d_L &= \frac{50}{e(309+53\gamma + \sqrt{(259)^2+3\gamma(19718+6403\gamma)}}, \end{aligned}$$

where $d_S < 0 < d_L < 1/e$ holds for $\gamma > \hat{\gamma}$. Thus, in the case of $\gamma > \hat{\gamma}$, $d > d_L$ ensures (A.1)> 0.

In the case of $\gamma < \hat{\gamma}$ (i.e. $\eta < 0$), the condition for (A.1)> 0 is $d'_S < d < d'_L$, where d'_S and d'_L are the smaller and the larger solution for (A.1)$= 0$.

$$\begin{aligned} d'_S &= \frac{50}{e(309+53\gamma + \sqrt{(259)^2+3\gamma(19718+6403\gamma)}}, \\ d'_L &= \frac{50}{e(309+53\gamma - \sqrt{(259)^2+3\gamma(19718+6403\gamma)}}, \end{aligned}$$

where $0 < d'_S < 1/e < d'_L$ holds for $\gamma < \hat{\gamma}$. From Assumption CT, we exclude $1/e < d$. Thus, in the case of $\gamma < \hat{\gamma}$, $d > d'_S$ ensures (A.1)> 0. The fact $d_L = d'_S \equiv \Psi$ proves $FI^{NT} \gtreqless FI^{CT} \Leftrightarrow d \gtreqless \Psi$.

From the fact that Ψ is strictly decreasing in γ, we can prove that $FI^{NT} > FI^{CT}$ is more likely to hold as γ becomes large.

Proof of Proposition 9: We obtain

$$FI^{NQ} - FI^{CQ} = \nu d^2 + \xi d + \varpi, \tag{A.2}$$

where

$$\nu = \frac{\{71 - 9\gamma(2+\gamma)\}e}{144} > 0, \quad \xi = \frac{1}{9} > 0, \quad \varpi = -\frac{1}{16e} < 0.$$

Thus, the condition for (A.2)>0 is $d < d''_S$ or $d > d''_L$, where d''_S and d''_L are the smaller and the larger solutions for $(A.2) = 0$.

$$d''_S = -\frac{8 + \sqrt{(19-9\gamma)(37+9\gamma)}}{e(71 - 9\gamma(2+\gamma))} < 0, \quad d''_L = \frac{\sqrt{(19-9\gamma)(37+9\gamma)} - 8}{e(71 - 9\gamma(2+\gamma))} > 0,$$

where $0 < d''_L \equiv \Omega < 1/\{(1+\gamma)e\}$ for all $\gamma \in [0,1]$. Thus, we have $FI^{NQ} \gtreqless FI^{CQ} \Leftrightarrow d \gtreqless \Omega$. Differentiating Ω in γ yields

$$\frac{d\Omega}{d\gamma} = \frac{729(1+\gamma)}{e\Delta(8+\Delta)^2} > 0,$$

where $\Delta \equiv \sqrt{(19-9\gamma)(37+9\gamma)} > 0$. Thus, we can prove that $FI^{NQ} > FI^{CQ}$ is more likely to hold as γ becomes small.

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