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RESEARCH ARTICLE

International R&D formations and strategic environmental policy

Takeshi Iida *

School of Global and Community Studies, University of Fukui, Fukui, Japan
*Corresponding author. E-mail: iida@u-fukui.ac.jp

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Abstract

We examine relations between strategic environmental policy, international R&D cartels and research joint ventures (RJVs), using a third-country model with Cournot duopoly. We indicate that forming an R&D/RJV cartel reduces governments' incentives to extract rent from consumers in the third country. Contrary to conventional wisdom, we find that social welfare under R&D cartels with full information sharing, i.e., RJV cartels, cannot surpass that under R&D/RJV competition, whereas forming an R&D/RJV cartel works well for environmental investment. Among the policy implications, we show that governments can maximize global welfare by collectively determining whether to allow R&D/RJV cartels.

Keywords: environmental R&D; international research joint venture; R&D cartel; strategic environmental policy

JEL classification: D43; F18; H23; L13; L24

1. Introduction

The literature reveals that environmental R&D cartels with full information sharing – that is, research joint venture cartels – internalize the public goods nature of knowledge generated by technology development and maximize social welfare. However, important international aspects of research joint venture (RJV) cartels, where firms in different countries cooperate on environmental R&D and governments act strategically, remain unanalyzed.

In international contexts under imperfect competition, governments distort environmental policies by acting strategically to obtain rent (Conrad, 1993; Barrett, 1994; Kennedy, 1994).[1] Therefore, researchers must consider the effects on strategic environmental policy when evaluating the performance of environmental RJV cartels in international contexts. This paper sheds light on this subject.[2]

[1] See the discussion of strategic environmental policy in Greaker (2013).

[2] Abe and Zhao (2005) considered international joint ventures with environmental externalities. They especially focused on environmental technology transfers from firms in developed countries to firms in developing countries through international joint ventures where participating firms share equity.

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We consider a third-country model that features Cournot duopoly. Two firms in different countries cooperate with environmental R&D and governments act strategically. The environmental technology we consider is end-of-pipe. Using this model reveals that three categories of incentives potentially distort environmental policy under R&D/RJV cartels: the *rent-shift effect*, the *over-investment effect*, and the *environmental spillover effect*. That is, governments have incentives to set lower environmental tax rates to obtain rents; to set lower tax rates to remedy 'over-investment by firms'; and to set higher tax rates to promote investment by rivals.

If the over-investment effect dominates, environmental taxation under an R&D/RJV cartel is below that under R&D/RJV competition, reducing rent extraction from consumers in the third county. Contrary to conventional wisdom, an RJV cartel cannot engender maximum social welfare, but RJV cartels work well for environmental investment.

In addition, promoting an R&D/RJV cartel could diminish consumer surplus in the third country if environmental tax under an R&D/RJV cartel exceeds that under R&D/RJV competition. Therefore, promoting an R&D/RJV cartel contradicts the aim of the competition policy that increases consumer surplus. This result is relevant to developing economies because environmental technology generally comes from developed economies and a developing economy may be the third country.

Our study shows that governments, including that of the third country, can maximize global welfare by coordinating decisions to allow international R&D cartels. International cooperative environmental R&D is expected to accelerate.[3] Therefore, this paper researches an important and timely topic and offers implications for environmental technology policy to tackle such global problems as climate change.

This paper proceeds as follows. Section 2 reviews the literature. Section 3 introduces the model. Section 4 analyzes R&D and RJV competition wherein firms decide R&D investment independently. Section 5 analyzes R&D and an RJV cartel wherein firms decide R&D investment jointly. Section 6 evaluates the performance of four R&D scenarios. Section 7 discusses our third-country model and extends it to firms that sell in all three countries. Section 8 concludes.

2. Related literature

Many studies in environmental economics investigate policy that promotes environmental R&D (Milliman and Prince, 1989; Denicolò, 1999; Montero, 2002). On the other hand, as a technology policy that solves problems caused by the public goods nature of knowledge,[4] arguments for cooperative R&D have been developed in the industrial

[3]For example, the Eco-Patent Commons launched in 2008 by IBM, Nokia, Sony and Pitney Bowes sought to promote international collaboration among firms in developing environmental technology by opening patent regimes (Hall and Helmers, 2013). The Paris Agreement of 2015 recommended collaborative action to develop environmental technology as a means to limit global warming to 2°C (see Article 10 of the Paris Agreement of 2015).

[4]The public goods nature of knowledge causes two market failures: the appropriability problem and information sharing market failure (Poyago-Theotoky, 2007). The appropriability problem is that innovators have incentives to under-invest in developing technology relative to the social optimum because they cannot draw the full benefit of R&D when information leaks. Moreover, the non-rival property of knowledge makes diffusing it desirable for social welfare. However, innovators lack incentive to share knowledge absent a reward (information-sharing market failure).

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organization literature (D'Aspremont and Jacquemin, 1988; Kamien et al., 1992; Amir et al., 2003).

RJV cartels in polluting industries are a current topic in the environmental economics literature. Petrakis and Poyago-Theotoky (2002) modeled an RJV cartel with R&D subsidies in a polluting industry based on D'Aspremont and Jacquemin (1988). Contrary to conventional wisdom, they show that R&D subsidies may be preferable to RJV cartels in the presence of environmental externalities. Sandonís and Mariel (2004) studied a case wherein R&D competition was preferable to an RJV cartel. However, technologies in both papers were targeted at reducing costs, not enlarging environmental benefits. Therefore, R&D investment only lowers marginal costs, stimulating the polluting activity. RJV cartels that pollute may erode social welfare.

Chiou and Hu (2001) considered R&D cartels under an exogenous environmental tax and technology that reduced pollution per unit of output. They showed that R&D cartels can permit firms to collude indirectly in product markets. However, RJV cartels enhance social welfare if the benefit from internalizing the positive externality (information leakage) is relatively large.

Poyago-Theotoky (2007) compared non-cooperative R&D with performance of an R&D cartel under an endogenous environmental tax when the government cannot commit to a tax rate. In her model, firms adopt end-of-pipe technology that does not alter production processes. Even if knowledge spillover is great, she showed that R&D cartels may erode social welfare compared to non-cooperative R&D, and cooperation is preferable to non-cooperation when knowledge spillover is perfect.

Ouchida and Goto (2016a) considered firms' endogenous choice to form R&D cartels and mirror the results in Poyago-Theotoky (2007). Ouchida and Goto (2016b) showed that R&D cartels enhance social welfare more than R&D competition when the government commits to an environmental tax rate.

Previous studies endorse environmental RJV cartels for social welfare, but they do not analyze contexts wherein firms in different countries cooperate and governments act strategically. This paper differs in examining strategic environmental policy when firms form R&D/RJV cartels. The literature on industrial organization considers two types of market failures; studies in environmental economics consider those plus market failures from environmental externalities. We examine strategic environmental policy under three types of market failures, and RJV cartels might not maximize social welfare in our model.

Ulph and Ulph (2007) investigated environmental R&D competition, environmental technology that reduced pollution per unit of output, R&D spillover between domestic firms, and R&D subsidies as technology policy. They showed that the government may tax R&D to suppress excessive competition. Our paper differs from theirs in considering R&D spillover between firms in different countries, end-of-pipe technology, and an international environmental R&D cartel.

El-Sayed and Rubio (2014) and Rubio (2017) analyzed cooperative R&D from the perspective of international environmental agreements but disregarded interaction between firms and governments.

3. The model

Consider a third-country model with two identical countries and two identical firms. Firms 1 and 2 are in countries 1 and 2, respectively. To simplify the analysis, we assume that firms produce final goods at marginal cost c=0.

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We assume that producing one unit of final goods generates one unit of emissions. An environmental damage function is given by $ED(e_i) = (\gamma/2)e_i^2$, where γ and e_i denote evaluation for the environment and total emissions caused by firm i, i=1,2, respectively.[5] We assume $\gamma \geq \frac{1}{2}$ to assure positive environmental taxes. The environmental damage function satisfies the conditions $\partial ED/\partial e_i > 0$ and $\partial^2 ED/\partial e_i^2 > 0$, which represent the typical relationship between total emissions and environmental damage as suggested by many environmental economists.

As we consider environmental R&D, total emissions are given by $e_i = q_i - x_i - \beta x_j$, where q_i, x_i, and $\beta \in [0, 1]$ are total polluting output, environmental R&D that mitigates pollution, and the spillover rate of technology, respectively, i=1,2, $i \neq j$. Therefore, when $\beta \neq 0$, firm i benefits from firm j's R&D effort by amount βx_j for emission reductions, i=1,2, $i \neq j$.

We assume the cost of environmental R&D to be $f(x_i) = \eta/2x_i^2$, i=1,2, where $\eta > 0$ represents efficiency of the environmental R&D technology. The inverse demand function is $p(q) = 1 - q$ where $q = q_1 + q_2$ is total output of firms 1 and 2. The inverse demand function satisfies $p''(q)q + p'(q) < 0$, which guarantees the second-order condition for profit maximization. Additionally, in our setting of the model, the equilibrium is unique.

The payoff functions of firm i and country i are, respectively, $\pi_i = pq_i - t_i e_i - f(x_i)$ and $SW_i = \pi_i + t_i e_i - ED(e_i)$, where $t_i e_i$ is the tax revenue, i=1,2. The property of a third-country model is that firms export all products to a third country, and consumer surplus can be ignored in the social welfare of country i, $i = 1, 2$.

We examine four R&D scenarios studied by Kamien *et al.* (1992):

- Scenario N: R&D competition. Firms compete during R&D given knowledge spillover $\beta \in [0, 1)$.
- Scenario C: R&D cartel. Firms determine R&D investment cooperatively to maximize joint profit given knowledge spillover $\beta \in [0, 1)$.
- Scenario NJ: RJV competition. Firms compete during R&D but share the outcome such that $\beta = 1$.
- Scenario CJ: RJV cartel. Firms determine R&D investment cooperatively to maximize joint profit and share the R&D outcome, therefore, $\beta = 1$.

We study a three-stage game to document the four scenarios. We construct a three-stage game for scenario N and NJ (R&D/RJV competition). At stage 1, countries 1 and 2 simultaneously set tax rates t_1 and t_2 to maximize their respective social welfares. At stage 2, firms decide their respective R&D investments (x_1 and x_2) independently to maximize individual profit. At stage 3, firms 1 and 2 determine their quantities of final goods (q_1 and q_2, respectively), and profits and social welfare result.

For scenario C and CJ (R&D/RJV cartel) the first and third stages repeat those of scenario N and NJ (R&D/RJV competition). However, at stage 2, firms form an environmental cartel and determine R&D to maximize joint profit $\pi_1 + \pi_2$.

For all scenarios we performed backward induction to find subgame perfect Nash equilibrium. We disregard cartel production because anti-monopoly laws prohibit it.[6]

[5] Although we disregard cross-border pollution, our results hold qualitatively if we consider it, such as $ED(e_1 + e_2)$.

[6] D'Aspremont and Jacquemin (1988) investigated cooperation during R&D and production.

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Although we analyze the models in the next section, equilibrium values for R&D/RJV competition and an R&D/RJV cartel appear in appendices A.1 and A.2, respectively.

4. R&D competition and RJV competition

At stage 3, the two firms choose q_1 and q_2 as their respective profit-maximizing outputs. We get

$$\frac{\partial \pi_i}{\partial q_i} = p'q_i + p - t_i = 0, \quad i = 1, 2. \tag{1}$$

From equation (1), we obtain equilibrium output as $q_i^* = \frac{1}{3}(1 - 2t_i + t_j)$, i=1,2, $i \neq j$.

At stage 2, firms independently decide the environmental R&D spending that maximizes their respective profits. We obtain

$$\frac{\partial \pi_i}{\partial x_i} = t_i - \frac{\partial f}{\partial x_i} = 0, \quad i = 1, 2. \tag{2}$$

Firm i decides what spending satisfies the condition that the marginal benefit of environmental R&D equals its marginal cost. From equation (2) and $\partial f / \partial x_i = \eta x_i$, we obtain equilibrium R&D as $x_i^N(t_i) = t_i/\eta$, i=1,2. Given that t_i is the marginal benefit of R&D, we get $\partial x_i^N / \partial t_i = 1/\eta > 0$. Benefits of environmental R&D come only from the reduced tax burden for end-of-pipe technologies.[7]

At stage 1, countries establish t_1 and t_2 as tax rates that maximize their respective social welfare:

$$SW_i^N = p(q^*)q_i^* - f(x_i^N) - ED(q_i^* - x_i^N - \beta x_j^N), \quad i, j = 1, 2, \ i \neq j.^{8}$$

We obtain

$$\frac{\partial SW_i^N}{\partial t_i} = (t_i - ED')\left(\frac{\partial q_i^*}{\partial t_i} - \frac{\partial x_i^N}{\partial t_i}\right) + \underbrace{p'\frac{\partial q_j^*}{\partial t_i}q_i^*}_{(-)} = 0, \quad i = 1, 2 \text{ and } i \neq j. \tag{3}$$

See appendix A.3 for the derivation of equation (3).

The optimal environmental tax is

$$t_i^N(\beta) = \frac{\eta(-\eta + \gamma(3 + 2\eta))}{\gamma(3 + 3\beta + \eta)(3 + 2\eta) + \eta(9 + 5\eta)}, \quad i = 1, 2.$$

When $\beta = 1$, we obtain the environmental tax under RJV competition as $t_i^{NJ} = t_i^N(1)$.

As the last term of equation (3) is negative, the equilibrium tax rate is sub-Pigouvian because countries have incentives to extract rent from the rival firm when they act strategically (*rent-shift effect*), as indicated in Ulph (1996).[9]

[7] Environmental R&D does not lower the marginal cost for producing end-of-pipe technology and therefore induces no competitive advantage. However, it induces competitive advantage by lowering the marginal cost of process innovations that reduce pollution per output. So firms have an incentive to spend excessively on environmental R&D (Ulph and Ulph, 2007).

[8] Note that environmental taxes paid by firm i are canceled out by tax revenue of country i.

[9] If governments can tax output and emissions, environmental taxes internalize the environmental externality, and output taxes shift rent. Therefore, the environmental tax is set at a Pigouvian level, and the output tax is negative.

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When β increases, the marginal environmental damage lessens through knowledge spillover. As a result, the optimal environmental tax decreases in β, and we get $\partial t_i^N/\partial\beta < 0$.

In the equilibrium, we get $x_i^N(\beta) = x_i^N(t_i^N(\beta))$ and $x_i^{NJ} = x_i^N(t_i^N(1))$. From $\partial x_i^N/\partial t_i > 0$ and $\partial t_i^N/\partial\beta < 0$, we obtain $\partial x_i^N(\beta)/\partial\beta = \partial x_i^N/\partial t_i(\partial t_i^N/\partial\beta) < 0$. Therefore, we obtain the following result.

Lemma 1 : *Environmental R&D is lower under RJV competition than under R&D competition. Therefore, we obtain* $x_i^{NJ} < x_i^N(\beta)$ *for* $\beta \in [0, 1)$, *i=1.2.*

5. R&D cartel and RJV cartel

The equilibrium output at stage 3 is the same as in the previous sections, and we obtain $q_i^* = \frac{1}{3}(1 - 2t_i + t_j)$, i=1,2 and $i \neq j$. At stage 2, however, firms 1 and 2 choose x_1 and x_2, respectively, as their R&D spending to maximize joint profit $\pi_1 + \pi_2$. We get

$$\frac{\partial[\pi_i + \pi_j]}{\partial x_i} = t_i + \beta t_j - \frac{\partial f}{\partial x_i} = 0, \quad i, j = 1, 2 \text{ and } i \neq j. \tag{4}$$

From equation (4), we obtain equilibrium environmental R&D as $x_i^C(t_i, t_j, \beta) = (t_i + \beta t_j)/\eta$.

Under an R&D/RJV cartel, firm i can receive the marginal benefit $t_i + \beta t_j$ from environmental R&D. Therefore, when firms form R&D/RJV cartels, they internalize knowledge spillover, which reduces a rival firm's tax burden. We thus obtain $\partial x_i^C(t_i, t_j, \beta)/\partial t_i = 1/\eta > 0$, $\partial x_i^C(t_i, t_j, \beta)/\partial t_j = \beta/\eta > 0$ and $\partial x_i^C(t_i, t_j, \beta)/\partial\beta = t_j/\beta > 0$; if the marginal benefit of environmental R&D increases, x_i^C increases.

At stage 1, countries 1 and 2 simultaneously establish t_1 and t_2, respectively, as welfare-maximizing environmental taxes. The social welfare of country i is $SW_i^C = p(q^*)q_i^* - f(x_i^C) - ED(q_i^* - x_i^C - \beta x_j^C)$, and we get

$$\frac{\partial SW_i^C}{\partial t_i} = (t_i - ED')\left(\frac{\partial q_i^*}{\partial t_i} - \frac{\partial x_i^C}{\partial t_i}\right) + p'\frac{\partial q_j^*}{\partial t_i}q_i \underbrace{-\beta t_j \frac{\partial x_i^C}{\partial t_i}}_{(-)} + \underbrace{\beta ED'\frac{\partial x_j^C}{\partial t_i}}_{(+)} = 0, \tag{5}$$

i=1,2 and $i \neq j$. See appendix A.3 for the derivation of equation (5).

The third and fourth terms in (5) differ from the examination of R&D/RJV competition (eqation (3)). The third term is the over-investment effect, which takes the tax rate beneath the Pigouvian level. Firms in R&D cartels consider benefits to rivals and increase R&D spending. From a social welfare perspective, however, that is over-investment. Therefore, governments set a lower tax rate to reduce R&D spending.[10]

The fourth term is the environmental spillover effect (Ulph and Ulph, 2007). The domestic environmental tax increases the rival firm's R&D through knowledge spillover,

[10]In Ulph and Ulph (2007), excessive R&D competition between firms via process innovation generates over-investment. In our model, firms adopt end-of-pipe technology and over-investment comes from the R&D/RJV cartel.

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which in turn reduces domestic pollution. Therefore, governments have an incentive to set a higher tax rate. Using equation (5), symmetrical.

$$t_i^C = ED' \frac{\frac{\partial q_i^*}{\partial t_i} - \frac{\partial x_i^C}{\partial t_i} - \beta \frac{\partial x_j^C}{\partial t_i}}{\frac{\partial q_i^*}{\partial t_i} - \frac{\partial x_i^C}{\partial t_i} - \beta \frac{\partial x_j^C}{\partial t_i}} - \frac{p' \frac{\partial q_j^*}{\partial t_i} q_i^*}{\frac{\partial q_i^*}{\partial t_i} - (1+\beta)\frac{\partial x_i^C}{\partial t_i}}, \quad i,j = 1,2 \text{ and } i \neq j. \tag{6}$$

In equation (6), the fact that $\partial x_i^C/\partial t_i = 1/\eta \geq \partial x_j^C/\partial t_i = \beta/\eta$ means that the first term is less than or equal to ED' because the numerator $\partial q_i^*/\partial t_i - \partial x_i^C/\partial t_i - \beta(\partial x_j^C/\partial t_i)$ is less than or equal to the denominator $\partial q_i^*/\partial t_i - \partial x_i^C/\partial t_i - \beta(\partial x_i^C/\partial t_i)$. In addition, the second term is positive. Therefore, we obtain $t_i^C < ED_i'$, meaning that the effects of rent-shift and over-investment dominate the environmental spillover effect.[11] The sign of $\partial t_i^C/\partial\beta$ is ambiguous.

In the equilibrium, we get $x_i^C(\beta) = x_i^C(t_i^C(\beta), t_j^C(\beta), \beta)$ and $x_i^{CJ} = x_i^C(t_i^C(1), t_j^C(1), 1)$, i=1,2, $i \neq j$.

6. Comparison of four R&D formations

This section investigates performance of an international R&D/RJV cartel. It derives policy implications of cooperative environmental R&D.

6.1. Comparison of environmental taxes

First we examine optimal environmental taxation under RJV competition and an RJV cartel.

Proposition 1: *When R&D efficiency is high (when $\eta \leq \sqrt{3}$) or environmental damage is large (when $\gamma \geq \max\{\frac{1}{2}, \gamma_{tNC}\}$), environmental tax under RJV competition exceeds taxation under an RJV cartel. When R&D efficiency is low (when $\eta > \sqrt{3}$) and environmental damage is small (when $\frac{1}{2} < \gamma < \gamma_{tNC}$), environmental tax under RJV competition is below that under an RJV cartel.*

Proof : We obtain

$$t_i^{NJ} - t_i^{CJ} = \frac{3\eta(8\gamma^2\eta^2 + 36\gamma^2\eta + 36\gamma^2 - 4\gamma\eta^2 - 18\gamma\eta - 3\eta^2)}{(2\gamma\eta^2 + 15\gamma\eta + 18\gamma + 5\eta^2 + 9\eta)(2\gamma\eta^2 + 30\gamma\eta + 72\gamma + 5\eta^2 + 18\eta)}, \quad i = 1,2.$$

Therefore, for any given η, the sign of $t_i^{NJ} - t_i^{CJ}$ is positive when γ is large. Then we obtain $\gamma_{tNC} = (2\eta^2 + \sqrt{28\eta^4 + 144\eta^3 + 189\eta^2} + 9\eta)/4(2\eta^2 + 9\eta + 9)$ which satisfies $t_i^{NJ} = t_i^{CJ}$, and $t_i^{NJ} > (<) t_i^{CJ}$ when $\gamma > (<)\gamma_{tNC}$. In addition, we obtain $\eta = \sqrt{3}$ which satisfies $\gamma_{tNC} = \frac{1}{2}$ and $\partial\gamma_{tNC}/\partial\eta > 0$ which leads to the result. □

Figure 1 depicts the result. The curve γ_{tNC} satisfies $t_i^{NJ} = t_i^{CJ}$, i=1,2.

[11] In this case, the environmental tax is sub-Pigouvian even if governments tax output because over-investment relates to R&D spending that cannot be remedied by any output tax.

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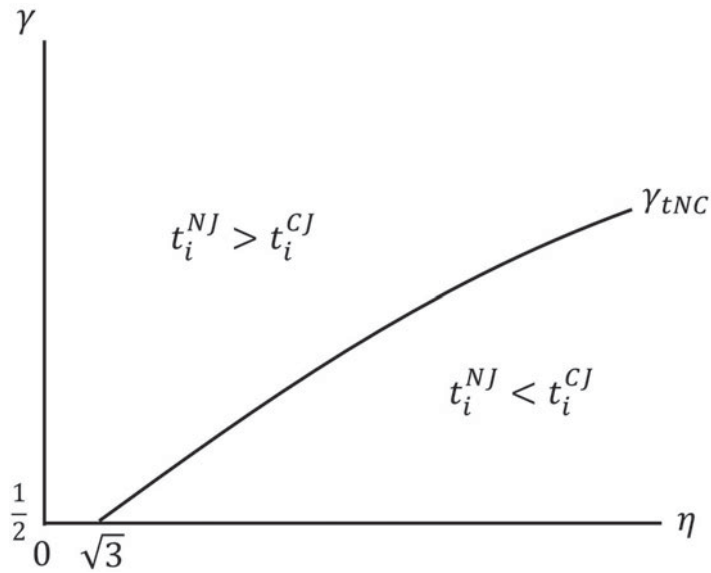


Figure 1. Proposition 1.

We explain our results as follows. Under R&D cartels, the sign of $\partial t_i^C/\partial\beta$ depends on the parameters β, η, and γ.[12] When R&D efficiency is high (when $\eta \leq \sqrt{3}$) or environmental damage is large (when $\gamma \geq \max\{\frac{1}{2}, \gamma_{tNC}\}$), environmental R&D is substantial and raises R&D spending. The over-investment effect is enhanced when β increases, and we obtain $\partial t_i^C/\partial\beta < 0$ followed by $t_i^{NJ} > t_i^{CJ}$.

For example, when $\eta = 1$ and $\gamma = 10$, we get $\partial t_i^C/\partial\beta < 0$ as depicted in the left panel of figure 2. In this case, governments rely on knowledge spillover to lessen environmental damage and set the lower tax rate to suppress R&D spending under an R&D/RJV cartel. Therefore, we obtain $t_i^{NJ} > t_i^{CJ}$.

When R&D efficiency is low (when $\eta > \sqrt{3}$) and environmental damage is small (when $\frac{1}{2} < \gamma < \gamma_{tNC}$), environmental R&D is subdued. Environmental spillover effects are enhanced when β is large to promote environmental R&D of rival firms. Therefore, we obtain $\partial t_i^C/\partial\beta > 0$ followed by $t_i^{NJ} < t_i^{CJ}$.

For example, when $\eta = 5$ and $\gamma = \frac{1}{2}$, then $\partial t_i^C/\partial\beta > 0$ when β is large as depicted in the right panel of figure 2. In this case, governments set a higher environmental tax to promote rival firms' R&D investment under an R&D/RJV cartel. Therefore, we obtain $t_i^{NJ} < t_i^{CJ}$.

[12]Note that under R&D competition, we get $\frac{\partial t_i^n}{\partial\beta} < 0$ for any η and γ (see section 4).

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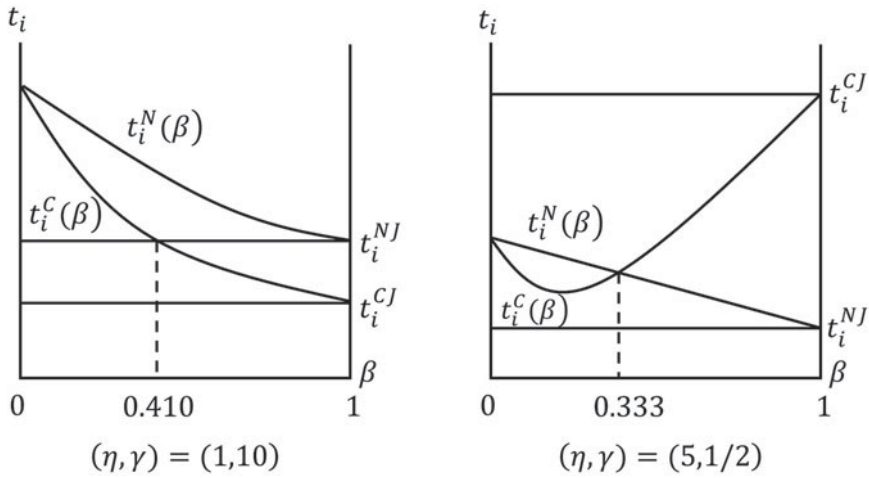


Figure 2. The relation between environmental tax and knowledge spillover.

6.2. Comparison of R&D investment

We compare R&D spending under R&D/RJV competition with that under an R&D/RJV cartel. From our assumption of $\partial f/\partial x_i > 0$ and from equations (2) and (4), we obtain $x_i^N \leq x_i^C$ if and only if $t_i^N \leq t_i^C + \beta t_j^C$.[13] We obtain the following result.

Proposition 2: *Environmental R&D is higher under an international R&D/RJV cartel than under R&D/RJV competition for any given* β. *Therefore, we obtain* $x_i^{CJ} > x_i^{NJ}$ *and* $x_i^C(\beta) \geq x_i^N(\beta)$ *for any given* $\beta \in [0,1)$, *i=1,2.*

The proof can be found in appendix A.4.

Previous literature shows that competition during R&D generates higher spending than cooperative R&D when knowledge spillover is small (D'Aspremont and Jacquemin, 1988; Chiou and Hu, 2001; Poyago-Theotoky, 2007; Ouchida and Goto, 2016a). However, in our model which features strategic environmental policy, incentive for R&D spending under an R&D/RJV cartel always exceeds that under R&D/RJV competition, even if knowledge spillover is small. Alongside the benefit of internalization of knowledge spillover, the environmental spillover effect – which enhances environmental taxes under R&D/RJV cartels – prompts this result.[14]

We also show that RJV cartels do not generate the highest R&D. We investigate how knowledge spillover affects R&D spending to show the result. In the case of R&D competition, we get $\partial x_i^N/\partial\beta < 0$ for any η and γ (see Lemma 1).

[13]Therefore, when $\beta = 0$, because $t_i^C(0) = t_i^N(0)$, we get $x_i^C(0) = x_i^N(0)$, i=1,2.

[14]Ouchida and Goto (2016b) show that R&D cartels prompt more environmental R&D than R&D competition even if knowledge spillover is small. However, they do not rank the four R&D scenarios.

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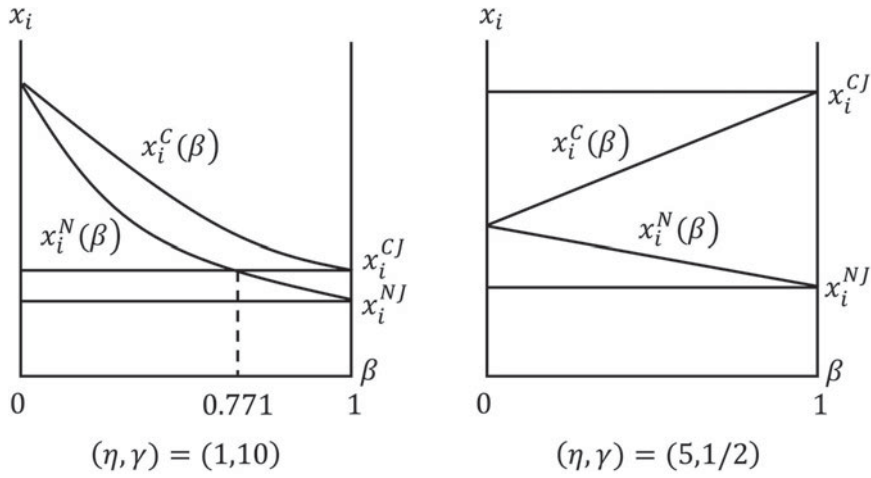


Figure 3. The relation between R&D investment and knowledge spillover.

However, in the case of R&D cartels, the sign of $\partial x_i^C/\partial\beta$ is ambiguous. To investigate the sign of $\partial x_i^C/\partial\beta$, we obtain this equation for i,j=1,2 and $i \neq j$:

$$\frac{\partial x_i^C(t_i^C(\beta), t_j^C(\beta), \beta)}{\partial\beta} = \underbrace{\frac{\partial x_i^C(t_i, t_j, \beta)}{\partial t_i}\frac{\partial t_i^C}{\partial\beta}}_{\text{indirect effect}} + \underbrace{\frac{\partial x_i^C(t_i, t_j, \beta)}{\partial t_j}\frac{\partial t_j^C}{\partial\beta}}_{\text{indirect effect}} + \underbrace{\frac{\partial x_i^C(t_i, t_j, \beta)}{\partial\beta}}_{\text{direct effect}(+)}. \quad (7)$$

The first and second terms of equation (7) represent the effect of β on environmental R&D via tax rates. We obtain $\partial x_i^C(t_i, t_j, \beta)/\partial t_i = 1/\eta > 0$, whereas $\partial t_i^C/\partial\beta$ depends on β, η and γ. Therefore, signs of indirect effects are ambiguous, but the direct effect (the third term) is positive. Therefore, $\partial x_i^C(t_i, t_j, \beta)/\partial\beta = t_j/\eta > 0$.

When R&D efficiency is high or environmental damage is large, over-spending leads to $\partial t_i^C/\partial\beta < 0$, which induces an indirect negative effect. In this case, we get $\partial x_i^C/\partial\beta < 0$ if indirect effects dominate the direct effect.

For example, when $\eta = 1$ and $\gamma = 10$, negative indirect effects dominate the positive direct effect, engendering $\partial x_i^C/\partial\beta < 0$ as depicted in the left panel of figure 3. In this case, the rankings of environmental R&D are $x_i^C(\beta) \geq x_i^N(\beta) > x_i^{CJ} > x_i^{NJ}$ when $0 \leq \beta < 0.771$, and $x_i^C(\beta) \geq x_i^{CJ} > x_i^N(\beta) > x_i^{NJ}$ when $0.771 \leq \beta < 1$. Therefore, RJV cartels do not generate the highest R&D.

On the other hand, when R&D efficiency is low and environmental damage is small, the environmental spillover effect leads to $\partial t_i^C/\partial\beta > 0$ when β is large. In this case, indirect effects become positive, and we obtain $\partial x_i^C/\partial\beta > 0$. For example, when $\eta = 5$ and $\gamma = \frac{1}{2}$, we obtain $\partial x_i^C/\partial\beta > 0$ as depicted in the right panel of figure 3. In this case, positive indirect effects and the direct effect generate the highest R&D under RJV cartels. Our result differs from that in D'Aspremont and Jacquemin (1988), where an RJV cartel generates the highest R&D.

Ouchida and Goto (2016a) showed that environmental R&D under an RJV cartel is below that under R&D competition. In their model, however, governments cannot

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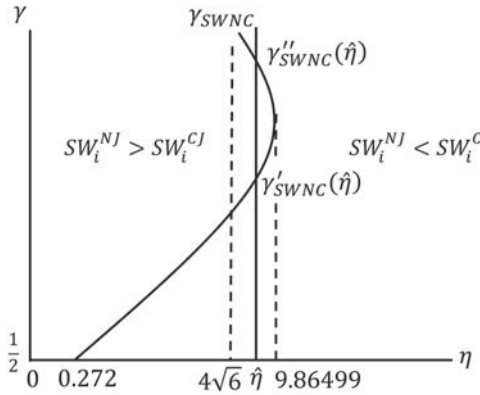


Figure 4. Proposition 3.

commit to a tax rate. Therefore, firms could affect tax rates. They chose higher environmental R&D to induce lower tax rates when competing during R&D. Firms cannot affect tax rates in our model.

6.3. Social welfare

Next, we compare social welfare under RJV competition and an RJV cartel.[15]

Proposition 3: *When* $0 < \eta \leq 4\sqrt{6}$, *we obtain* $SW_i^{NJ} \geq SW_i^{CJ}$ *if* $\gamma \geq \max\{\frac{1}{2}, \gamma_{SWNC}\}$, $i = 1, 2$. *When* $4\sqrt{6} < \eta \leq 9.86499$, *we obtain* $SW_i^{NJ} \geq SW_i^{CJ}$ *if* $\gamma'_{SWNC} \leq \gamma \leq \gamma''_{SWNC}$, $i = 1, 2$. *Otherwise, we obtain* $SW_i^{NJ} < SW_i^{CJ}$, $i = 1, 2$.

The proof is in appendix A.5.

Therefore, the highest environmental R&D under an RJV cartel does not always maximize social welfare. Figure 4 depicts the result for the (η, γ) space. The curve γ_{SWNC} satisfies $SW_i^{NJ}(\eta, \gamma) = SW_i^{CJ}(\eta, \gamma)$, i=1,2. Moreover, when $4\sqrt{6} < \eta < 9.86499$, we obtain $\gamma'_{SWNC}(\hat{\eta})$ and $\gamma''_{SWNC}(\hat{\eta})$ such that $SW_i^{NJ}(\hat{\eta}, \gamma) = SW_i^{CJ}(\hat{\eta}, \gamma)$ for a given $\hat{\eta} \in (4\sqrt{6}, 9.86499)$ where $\gamma'_{SWNC} < \gamma''_{SWNC}$.

The following is the intuition of the result. Comparing social welfares, we obtain

$$SW_i^{CJ} - SW_i^{NJ} = \underbrace{[p^{CJ}q_i^{CJ} - p^{NJ}q_i^{NJ}]}_{\Delta TR(?)} \underbrace{-[f(x_i^{CJ}) - f(x_i^{NJ})]}_{\Delta f(-)} \underbrace{-[ED_i^{CJ} - ED_i^{NJ}]}_{\Delta ED(+)}. \quad (8)$$

Given that $x_i^C(\beta) \geq x_i^N(\beta)$ and $\partial f / \partial x_i > 0$, the second term (difference in R&D cost) in equation (8) is negative. An RJV cartel entails a cost. Also, the last term in equation (8) is positive for any parameter in our specification. Therefore, less environmental damage is one benefit of an RJV cartel. Only the first term (difference in total revenue) in equation (8) is ambiguous.

[15]We only consider the case of $\beta = 1$ because illustrating the case $\beta \in |0, 1)$ complicates the exposition. In addition, social welfare is maximized when firms form RJV competition or an RJV cartel.

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When $0 < \eta \leq 4\sqrt{6}$ and $\gamma \geq \max\{\frac{1}{2}, \gamma_{SWNC}\}$, or when $4\sqrt{6} < \eta \leq 9.86499$ and $\gamma'_{SWNC} \leq \gamma \leq \gamma''_{SWNC}$, the over-investment effect and lesser environmental damage under an RJV cartel lead to $t_i^{NJ} > t_i^{CJ}$, which can result in $\Delta TR < 0$. Therefore, environmental tax under an RJV cartel is excessively low with respect to rent extraction. As a result, we obtain $SW_i^{NJ} > SW_i^{CJ}$ even if $x_i^{NJ} < x_i^{CJ}$.

In general, RJV cartels maximize social welfare (D'Aspremont and Jacquemin, 1988; Kamien et al., 1992; Chiou and Hu, 2001; Poyago-Theotoky, 2007; Ouchida and Goto, 2016a,b), because it internalizes two market failures caused by the public goods nature of knowledge. However, in international contexts where firms in different countries cooperate on environmental R&D and governments act strategically, RJV cartels may not engender the highest social welfare.

6.4. Global welfare

Although we show the case of $SW_i^{NJ} \geq SW_i^{CJ}$, RJV cartels may be preferable to RJV competition from a global welfare perspective that includes consumer surplus in the third country.[16] We only show that social and global welfare conflict under the case of $\beta = 1$.

First, we define social welfare of the third country as $SW_3^k = CS^k = \frac{1}{2}(q_1^k(t_1^k, t_2^k) + q_2^k(t_1^k, t_2^k))^2$, where CS^k represents consumer surplus and k=N,NJ,C,CJ. From equation (2), we get $q_1^k + q_2^k = \frac{1}{3}(2 - t_1^k - t_2^k)$, k=N,NJ,C,CJ. Therefore, we obtain $SW_3^{NJ} \leq (>) SW_3^{CJ}$ if and only if $t_i^{NJ} \geq (<) t_i^{CJ}$.

Now, we consider global welfare (GW) as the summed social welfare of the three countries. Therefore, $GW^k = SW_1^k + SW_2^k + SW_3^k$, $k = N, NJ, C, CJ$.

Proposition 4: *When $\gamma \geq \max\{\frac{1}{2}, \gamma_{GWNC}\}$, we obtain $GW^{NJ} \leq GW^{CJ}$. Otherwise, we obtain $GW^{NJ} > GW^{CJ}$.*

The proof can be found in appendix A.6.

Figure 5 depicts results for the (η, γ) space. The curve γ_{GWNC} satisfies $GW^{NJ}(\eta, \gamma) = GW^{CJ}(\eta, \gamma)$. Figure 5 also depicts γ_{SWNC} which appeared in figure 4. Therefore, when $0 < \eta \leq 4\sqrt{6}$ and $\gamma \geq \max\{\frac{1}{2}, \gamma_{SWNC}\}$, or when $4\sqrt{6} < \eta \leq 9.86499$ and $\gamma'_{SWNC} \leq \gamma \leq \gamma''_{SWNC}$, we obtain $SW_i^{NJ} \geq SW_i^{CJ}$ for i=1,2, whereas $GW^{NJ} < GW^{CJ}$. However, when $\frac{1}{2} < \gamma < \gamma_{GWNC}$, we obtain $SW_i^{NJ} < SW_i^{CJ}$ for i=1,2, whereas $GW^{NJ} > GW^{CJ}$. Then, we derive policy implications for an international RJV cartel.

Proposition 5: *When R&D efficiency is high and environmental damage is large (when $0 < \eta \leq 4\sqrt{6}$ and $\gamma \geq \max\{\frac{1}{2}, \gamma_{SWNC}\}$ or when $4\sqrt{6} < \eta \leq 9.86499$ and $\gamma'_{SWNC} \leq \gamma \leq \gamma''_{SWNC}$), governments – including that of the third country – achieve higher global welfare by promoting RJV cartels. When R&D efficiency is low and environmental damage is small (when $\eta > 16.28$ and $\frac{1}{2} < \gamma < \gamma_{GWNC}$), governments enlarge global welfare by prohibiting RJV cartels.*

This result is obtained from propositions 3 and 4.

[16] Walz and Wellisch (1997) show that free trade is preferable to export subsidies in a third-country model because higher tax rates under free trade raise product prices, diminishing consumer surplus in the third country.

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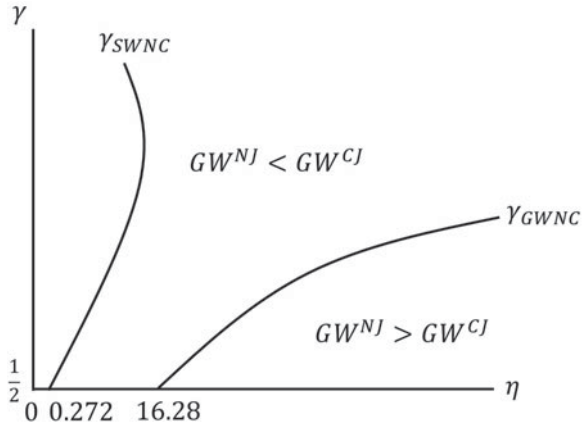


Figure 5. Propositions 4 and 5.

Therefore, RJV cartels seem preferable to RJV competition for global welfare even if $SW_i^{NJ} \geq SW_i^{CJ}$, but that is not always so. If an RJV cartel diminishes consumer surplus in the third country, promoting it contradicts the competition policy perspective.

Governments have recently promoted cooperative R&D to encourage international competitiveness, going so far as providing special antitrust treatment for it.[17] In addition, technology development and diffusion of environmental technology are indispensable for solving long-term environmental problems such as global warming. Therefore, banning RJV cartels may not serve the best interests of governments. If a strategic environmental policy exists, governments face tradeoffs between global welfare, especially consumer surplus in the third country, and promotion of environmental R&D. Therefore, our results suggest that governments, including that of the third country, should cooperate to determine whether to allow an R&D/RJV cartel.

6.5. Firms' incentives to form R&D/RJV cartels

Finally, we note firms' incentives to form R&D/RJV cartels. Comparing joint profit under R&D/RJV competition with that under an R&D/RJV cartel, we obtain $\pi_1^C(t_1, t_2, \beta) + \pi_2^C(t_1, t_2, \beta) - (\pi_1^N(t_1, t_2, \beta) + \pi_2^N(t_1, t_2, \beta)) = \beta^2(t_1^2 + t_2^2)/2\eta > 0$. Therefore, firms always choose R&D/RJV cartels for any given $\beta \in [0.1]$ when governments set environmental taxes before firms choose an R&D scenario.

However, if we consider a 'no commitment' case in which governments set environmental taxes after firms choose an R&D scenario, firms might not choose an R&D/RJV cartel. Absent governmental commitment, firms can affect environmental taxes. Therefore, firms may choose R&D/RJV competition expecting a higher environmental tax because it induces higher revenue than an R&D/RJV cartel.[18]

On the other hand, in the model of Poyago-Theotoky (2007), firms always have an incentive to form R&D/RJV cartels absent governmental commitment. Therefore, in

[17] For example, the National Cooperative Research and Production Act of 1993 in the US reduces antitrust exposure for cooperative R&D and production (Scott, 2008).

[18] For example, when $\eta = 1$ and $\gamma = 10$, we obtain $\pi_i^{CJ} - \pi_i^{NJ} = -0.004136$.

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Table 1. Comparisons, where $p_i = a - b(q_{i1} + q_{i2})$, i=1,2, and $p_3 = c - d(q_{31} + q_{32})$

Market size	Results of comparisons
(A) a=b=c=d=1	$t_i^{NJ} > t_i^{CJ}, x_i^{NJ} < x_i^{CJ}, SW_i^{NJ} < SW_i^{CJ}, GW^{NJ} < GW^{CJ}$
(B) a=1,b=4, c=d=2	$t_i^{NJ} \geq t_i^{CJ}$ when $\gamma \geq \max\{\frac{1}{2}, \gamma'_{tNC}\}$, otherwise $t_i^{NJ} < t_i^{CJ}$
	$x_i^{NJ} < x_i^{CJ}$
	$SW_i^{NJ} \geq SW_i^{CJ}$ when $\gamma \geq \max\{\frac{1}{2}, \gamma'_{SWNC}\}$, otherwise $SW_i^{NJ} < SW_i^{CJ}$
	$GW^{NJ} \leq GW^{CJ}$ when $\gamma \geq \max\{\frac{1}{2}, \gamma'_{GWNC}\}$, otherwise $GW^{NJ} > GW^{CJ}$

international contexts where strategic environmental policy exists, governments should commit to the tax rate if they want to control cooperative R&D among firms.

7. Model extension

We now consider the case in which firms supply their products to markets in Country 1 and Country 2 plus the third country. We explain that our main result holds if the market of Country 3 exceeds that of Country 1 and Country 2. We assume the inverse demand function of Country i is $p_i = a - b(q_{i1} + q_{i2})$, i=1,2, and that of Country 3 is $p_3 = c - d(q_{31} + q_{32})$. The sign q_{ij} represents the quantity of product firm j supplied to Country i, i=1,2,3 and j=1,2. The sign a, b and c,d represents market size of Countries 1, 2, and Country 3, respectively. We assume that the market sizes of Country 1 and 2 are identical. If $a<c$ and $b>d$, the market size of Country i, i=1,2, is smaller than that of Country 3.

The social welfare of Country i is $SW_i = (b/2)(q_{i1} + q_{i2})^2 + \pi_i + t_i(\sum_{k=1}^{3} q_{ki} - x_i - \beta x_j) - ED(\sum_{k=1}^{3} q_{ki} - x_i - \beta x_j)$, where $\pi_i = \sum_{k=1}^{3} p_k q_{ki} - t_i(\sum_{k=1}^{3} q_{ki} - x_i - \beta x_j) - f(x_i)$, i,j=1,2, $i \neq j$. Therefore, the social welfare of Country i includes consumer surplus. The social welfare of Country 3 is $SW_3 = (d/2)(q_{31} + q_{32})^2$.

We investigate two cases: (A) the market sizes of the three countries are the same, and a=b=c=d=1; (B) the market size of Country 3 exceeds that of Countries 1 and 2, and a=1,b=4,c=d=2. The result appears in table 1. Equilibrium values for case (A) and case (B) appear in the online appendix.

In case (A), we obtain $t_i^{NJ} > t_i^{CJ}$ and $SW_i^{NJ} < SW_i^{CJ}$ for any $\eta > 0$ and $\gamma \geq \frac{1}{2}$, which differs from results for propositions 1 and 3. On the other hand, in case (B), we obtain qualitatively the same result as with propositions 1, 2, 3, 4, and 5.[19]

Intuition for the result is as follows. When consumer surplus is included in social welfare, environmental taxes remedy distortions of imperfect competition.[20] If the market sizes of the three countries are identical, the government's incentive to remedy the distortion of imperfect competition cancels out the effect of strategic environmental policy (Greaker, 2013). In addition, environmental damage under an RJV cartel is below that under RJV competition. As a result, we obtain $t_i^{NJ} > t_i^{CJ}$. Then we obtain $SW_i^{NJ} < SW_i^{CJ}$ even if $t_i^{NJ} > t_i^{CJ}$, because the benefit of rent extraction is less than the loss of consumer surplus in its own country.

[19]The signs of γ'_{tNC}, γ'_{SWNC} and γ'_{GWNC} satisfy $t_i^{NJ} = t_i^{CJ}, SW_i^{NJ} = SW_i^{CJ}$ and $GW^{NJ} = GW^{CJ}$, respectively. Then, we can obtain figures similar to figures 1, 4 and 5.

[20]The incentive of governments to set a lower environmental tax to remedy the distortion of imperfect competition is added in equations (3) and (5), respectively.

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However, if the market of Country 3 is large, the effects of strategic environmental policy appear and we obtain the same result as with propositions 1, 2, 3, 4, and 5.

8. Conclusions

This paper examined relations between strategic environmental policy, international R&D cartels, and RJV using a third-country model featuring Cournot duopoly. We found that governments have three incentives that distort environmental policy when firms form an international R&D/RJV cartel. We derive three implications for international environmental technology policy.

First, and contrary to conventional wisdom, RJV cartels do not necessarily maximize social welfare. We show that strategic environmental policy (over-investment effect) reduces social welfare under an RJV cartel compared to RJV competition, whereas environmental investment under an R&D/RVJ cartel is higher than under R&D/RJV competition. Therefore, there are tradeoffs between social welfare and environmental R&D.

Second, governments, including that of the third country, can enhance global welfare if they collectively decide whether to allow R&D/RJV cartels. Collective decision-making enhances consumer surplus in the third country.

Finally, in international contexts where strategic environmental policy exists, governments should commit to an environmental tax rate to promote forming R&D/RJV cartels.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/S1355770X20000145

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Appendix

A.1 R&D/RJV competition

In equilibrium, we obtain the equilibrium values as follows:

$$q_i^N = \frac{(\gamma + \beta\gamma + \eta)(3 + 2\eta)}{\gamma(3 + 3\beta + \eta)(3 + 2\eta) + \eta(9 + 5\eta)},$$
$$x_i^N = \frac{(-\eta + \gamma(3 + 2\eta))}{\gamma(3 + 3\beta + \eta)(3 + 2\eta) + \eta(9 + 5\eta)},$$
$$\pi_i^N = \frac{A + \gamma^2(2\eta + 3)^2(2\beta^2 + 2\beta(\eta + 2) + \eta + 2) + \eta^2((2\beta + 25)\eta + 8\eta^2 + 18)}{2(\gamma(2\eta + 3)(3\beta + \eta + 3) + \eta(5\eta + 9))^2}, \tag{A1}$$

and

$$SW_i^N = \frac{\left(\eta^2\left(18 + 17\eta + 4\eta^2\right) + \gamma^2(3 + 2\eta)^2\left(2 + 2\beta^2 + \eta + 2\beta(2 + \eta)\right) + \gamma B\right)}{2(\gamma(3 + 3\beta + \eta)(3 + 2\eta) + \eta(9 + 5\eta))^2},$$

where $A \equiv 2\gamma\eta(2\eta + 3)(2\beta(\eta + 3) + 3(\eta + 2))$ and $B \equiv \eta(36 + 50\eta - \beta^2\eta + 24\eta^2 + 4\eta^3 + \beta(36 + 34\eta + 8\eta^2))$, and i=1,2.

Note that global welfare is obtained as $GW^N = \frac{1}{2}(q_1^N + q_2^N)^2 + SW_1^N + SW_2^N$.

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A.2 R&D/RJV cartel

The optimal environmental tax under an R&D/RJV cartel is obtained as follows:

$$t_i^C = \frac{\eta\left(-\eta+\gamma\left(3+3\beta^2+2\eta\right)\right)}{\begin{array}{c}\eta(9+9\beta+5\eta)\\ +\gamma\left(9+18\beta^3+9\beta^4+9\eta+2\eta^2+9\beta^2(2+\eta)+6\beta(3+2\eta)\right)\end{array}}, \quad i=1,2.$$

Then, we obtain the equilibrium values for i=1,2 as follows:

$$\begin{aligned} q_i^C &= \frac{1}{3}\left(1-\frac{\eta\left(1-\eta+\gamma\left(3+3\beta^2+2\eta\right)\right)}{\begin{array}{c}\eta(9+9\beta+5\eta)\\ +\gamma\left(9+18\beta^3+9\beta^4+9\eta+2\eta^2+9\beta^2(2+\eta)+6\beta(3+2\eta)\right)\end{array}}\right),\\ x_i^C &= \frac{(1+\beta)\left(-\eta+\gamma\left(3+3\beta^2+2\eta\right)\right)}{\eta(9+9\beta+5\eta)+\gamma\left(9+18\beta^3+9\beta^4+9\eta+2\eta^2+9\beta^2(2+\eta)+6\beta(3+2\eta)\right)}, \qquad \text{(A2)}\\ \pi_i^C &= \frac{\left(D+6(1+\beta)^2\gamma G+\eta^2\left(18+25\eta+8\eta^2+\beta^2(18+\eta)+\beta(36+26\eta)\right)\right)}{\begin{array}{c}2\left(\eta(9+9\beta+5\eta)\right.\\ \left.+\gamma\left(9+18\beta^3+9\beta^4+9\eta+2\eta^2+9\beta^2(2+\eta)+6\beta(3+2\eta)\right)\right)^2\end{array}}, \end{aligned}$$

where $D \equiv (1+\beta)^2\gamma^2(2+4\beta+2\beta^2+\eta)(3+3\beta^2+2\eta)^2$,

$$SW_i^C = \frac{\left(D+\eta^2\left(18-\beta^2(-18+\eta)+17\eta+4\eta^2+4\beta(9+4\eta)\right)+\gamma H\right)}{\begin{array}{c}2\left(\eta(9+9\beta+5\eta)\right.\\ \left.+\gamma\left(9+18\beta^3+9\beta^4+9\eta+2\eta^2+9\beta^2(2+\eta)+6\beta(3+2\eta)\right)\right)^2\end{array}},$$

where $G \equiv \eta(6+6\beta^3+7\eta+2\eta^2+3\beta^2(2+\eta)+\beta(6+4\eta))$, and $H \equiv \eta(36+36\beta^5+50\eta+24\eta^2+4\eta^3+16\beta^3(9+5\eta)+\beta^4(108+23\eta)+3\beta^2(48+35\eta+8\eta^2)+2\beta(54+49\eta+12\eta^2))$.

Note that global welfare is obtained as $GW^C = \frac{1}{2}(q_1^C+q_2^C)^2 + SW_1^C + SW_2^C$.

A.3 Derivation of equations (3) and (5)

Country i chooses t_i to maximize the social welfare SW_i^N, and we get

$$\frac{\partial SW_i^N}{\partial t_i} = (p'q_i^*+p^*)\frac{\partial q_i^*}{\partial t_i} + p'\frac{\partial q_j^*}{\partial t_i}q_i^* - \frac{\partial f}{\partial x_i}\frac{\partial x_i^N}{\partial t_i} - ED'\left(\frac{\partial q_i^*}{\partial t_i}-\frac{\partial x_i^N}{\partial t_i}\right) = 0,$$

i,j=1,2 and $i \neq j$. From equations (1) and (2), we get $p'q_i^* + p^* = t_i$ and $\partial f/\partial x_i = t_i$, respectively. As a result, we get equation (3).

Country i chooses t_i to maximize the social welfare SW_i^C, and we get

$$\frac{\partial SW_i^C}{\partial t_i} = (p'q_i^*+p^*)\frac{\partial q_i^*}{\partial t_i} + p'\frac{\partial q_j^*}{\partial t_i}q_i^* - \frac{\partial f}{\partial x_i}\frac{\partial x_i^C}{\partial t_i} - ED'\left(\frac{\partial q_i^*}{\partial t_i}-\frac{\partial x_i^C}{\partial t_i}-\beta\frac{\partial x_j^C}{\partial t_i}\right) = 0,$$

i,j=1,2 and $i \neq j$. From equations (1) and (4), we obtain $p'q_i^* + p^* = t_i$ and $\partial f/\partial x_i = t_i + \beta t_j$, respectively. As a result, we get equation (5).

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A.4 Proof of proposition 2

Using equations (A1) and (A2), we obtain

$$x_i^C - x_i^N = \frac{\beta\eta(J - \eta^2(5 - 8\gamma - 4\gamma^2))}{(6\beta\gamma\eta + 9\beta\gamma + 2\gamma\eta^2 + 9\gamma\eta + 9\gamma + 5\eta^2 + 9\eta)K},$$

where $J \equiv 9\beta^3\gamma + 6\beta^2\gamma^2\eta + 9\beta^2\gamma^2 + 15\beta^2\gamma\eta + 45\beta^2\gamma + 18\beta\gamma\eta + 36\beta\gamma + 12\gamma^2\eta + 9\gamma^2 + 12\gamma\eta$ and $K \equiv 9\beta^4\gamma + 18\beta^3\gamma + 9\beta^2\gamma\eta + 18\beta^2\gamma + 12\beta\gamma\eta + 18\beta\gamma + 9\beta\eta + 2\gamma\eta^2 + 9\gamma\eta + 9\gamma + 5\eta^2 + 9\eta$. Also, we obtain $J>0$, $K>0$ and $-\eta^2(5 - 8\gamma - 4\gamma^2) \geq 0$ when $\gamma \geq \frac{1}{2}$. Therefore, we obtain $x_i^C(\beta) \geq x_i^N(\beta)$ for $\beta \in [0, 1]$.

A.5 Proof of proposition 3

Comparing SW_i^{NJ} with SW_i^{CJ}, we obtain

$$SW_i^{NJ} - SW_i^{CJ} = \frac{-\eta(L + M + O + Q)}{2\left(2\gamma\eta^2 + 15\gamma\eta + 18\gamma + 5\eta^2 + 9\eta\right)^2\left(2\gamma\eta^2 + 30\gamma\eta + 72\gamma + 5\eta^2 + 18\eta\right)^2}, \quad \text{(A3)}$$

where $L = \gamma(196\eta^3 + 1881\eta^2 + 6588\eta + 7128)\eta^3 + 3(5\eta^2 + 66\eta + 108)\eta^4 > 0$, $M = 4\gamma^4(\eta^2 - 96)(2\eta^2 + 9\eta + 9)^2$, $O = 3\gamma^2\eta^2(-8\eta^4 + 420\eta^3 + 4183\eta^2 + 12996\eta + 12636)$ and $Q = 12\gamma^3\eta(-30\eta^4 - 49\eta^3 + 1017\eta^2 + 4122\eta + 4212)$.

Because the denominator of equation (A3) is positive, we obtain $\text{sign}[SW_i^{NJ} - SW_i^{CJ}] = \text{sign}[-\eta(L + M + O + Q)]$. Therefore, we investigate the sign of $L+M+O+Q$.

When $\gamma = \frac{1}{2}$, we obtain $L + M + O + Q \leq (>)0$ if $\eta \leq (>)0.272$. Therefore, when $\gamma = \frac{1}{2}$, we obtain $SW_i^{NJ} \geq (<)SW_i^{CJ}$ if $\eta \leq (>)0.272$, i=1,2.

On the other hand, when $\gamma \to \infty$, we obtain $L + M + O + Q = (\eta^2 - 96)(2\eta^2 + 9\eta + 9)^2\infty$. Therefore, when $\gamma \to \infty$, we obtain $L + M + O + Q \leq (>)0$ if $\eta \leq (>)4\sqrt{6}$. This result comes from the effect of M because the degree of M about γ is the largest compared to L, O and Q. Therefore, when γ is sufficiently large, the sign of M dominates the signs of L, O and Q. When $\eta < (>)4\sqrt{6}$, we obtain $M < (>)0$ and $\partial M/\partial\gamma < (>)0$. As a result, when γ is sufficiently large, we obtain $L + M + O + Q < 0$ for any given $\eta < 4\sqrt{6}$, and $L+M+O+Q>0$ for any given $\eta > 4\sqrt{6}$.

Note that the effect of sign M depends on the size of η. When η approaches $4\sqrt{6}$, M becomes 0. Therefore, when η is sufficiently smaller than $4\sqrt{6}$ or η is sufficiently larger than $4\sqrt{6}$, the effect of M is large. When $\eta = 0$, we obtain $M + L + O + Q < 0 (M = -31104\gamma^4$ and $L = O = Q = 0)$ for any $\gamma \geq \frac{1}{2}$. Therefore, when η is small, especially when $\eta \leq 0.272$, we obtain $M + L + O + Q \leq 0$ for any $\gamma \geq \frac{1}{2}$.

Next, we consider the range of $0.272 < \eta \leq 4\sqrt{6}$. When η approaches $4\sqrt{6}$, M becomes 0. In this case, the signs of L, O and Q are important. When $\eta = 4\sqrt{6}$, we obtain M=0, $L = 384\sqrt{6}(101616\sqrt{6} + 187704)\gamma + 27648(264\sqrt{6} + 588) > 0$, $O = 288(213264\sqrt{6} + 340476)\gamma^2 > 0$ and $Q = -48\sqrt{6}(2328\sqrt{6} + 174636)\gamma^3 < 0$. Therefore, in this case, if $\gamma = 0$, we obtain $L>0$, O=0 and Q=0. As a result, when $\eta = 4\sqrt{6}$, we obtain $L+M+O+Q>0$ if γ is sufficiently small. However, when γ increases, because the degree of Q about γ is the largest compared to L and O, the sign of $Q<0$ dominates the signs of $L>0$ and $O>0$. Therefore, when $\eta = 4\sqrt{6}$, we obtain $L+M+O+Q<0$ if γ is sufficiently large.

As a result, when $0.272 < \eta \leq 4\sqrt{6}$, we obtain $\gamma_{SWNC}(\eta)$ such that $L+M+O+Q$=0, and $L + M + O + Q < (>)0$ when $\gamma > (<)\gamma_{SWNC}(\eta)$. In addition, when η approaches $4\sqrt{6}$,

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because the effect of M that induces $L+M+O+Q<0$ becomes small, the large γ is required to obtain $L+M+O+Q<0$. Therefore, we obtain $\partial\gamma_{SWNC}/\partial\eta > 0$ when $0.272 < \eta \leq 4\sqrt{6}$, as depicted in figure 4.

Next we consider the range of $\eta > 4\sqrt{6}$. When $\eta = 4\sqrt{6} + \varepsilon$, where $\varepsilon > 0$ is sufficiently small, we obtain $L>0$, $M>0$, $O>0$ and $Q<0$. In this case, as argued above, we obtain $L + M + O + Q > 0$ when γ is sufficiently small, and $L+M+O+Q>0$ when γ is sufficiently large. However, when γ is in a certain range, we obtain $L+M+O+Q<0$. This is because the effect of $Q<0$ dominates the signs of $L>0$, $M>0$ and $O>0$. For example, when $\eta = 9.8$, we obtain $L+M+O+Q<0$ when $13.291 < \gamma < 1573.97$. However, when $\eta \geq 9.86499$, we obtain $L + M + O + Q \geq 0$ for any γ.

As a result, for a given $\hat{\eta} \in (4\sqrt{6}, 9.86499)$, we obtain $\gamma'_{SWNC}(\hat{\eta})$ and $\gamma''_{SWNC}(\hat{\eta})$ such that $L+M+O+Q=0$, where $\gamma'_{SWNC}(\hat{\eta}) < \gamma''_{SWNC}(\hat{\eta})$, and $L+M+O+Q<0$ when $\gamma'_{SWNC}(\hat{\eta}) < \gamma < \gamma''_{SWNC}(\hat{\eta})$. Otherwise, we obtain $L+M+O+Q>0$. Therefore, when $4\sqrt{6} < \eta < 9.86499$, $\gamma_{SWNC}(\eta)$ becomes a backward-bending curve as depicted in figure 4.

Finally, when $\eta \geq 9.86499$, we obtain $L + M + O + Q \geq 0$ for any γ because the effect of $M>0$ is large. Indeed, when $\eta \to \infty$, we obtain $(16\gamma^4 - 24\gamma^2 + 196\gamma + 15)\infty > 0$ for any $\gamma \geq 0$.

A.6 Proof of proposition 4

Comparing GW^{NJ} with GW^{CJ}, we obtain

$$GW^{NJ} - GW^{CJ} = \frac{-\eta(R + S + T + U + W)}{\left(2\gamma\left(\eta^2 + 15\eta + 36\right) + \eta(5\eta + 18)\right)^2\left(\gamma\left(2\eta^2 + 15\eta + 18\right) + \eta(5\eta + 9)\right)^2}, \quad \text{(A4)}$$

where $R = 4\gamma^4(\eta^2 + 24\eta + 96)(2\eta^2 + 9\eta + 9)^2 > 0$, $S = -3\eta^4(35\eta^2 + 132\eta + 108) < 0$, $T = -3\gamma\eta^3(4\eta^3 + 213\eta^2 + 588\eta + 216) < 0$, $U = \gamma^2\eta^2(232\eta^4 + 2508\eta^3 + 9765\eta^2 + 19332\eta + 17172) > 0$, and $W = 4\gamma^3\eta(32\eta^5 + 678\eta^4 + 4821\eta^3 + 15795\eta^2 + 25326\eta + 16524) > 0$.

Because the denominator of equation (A4) is positive, we obtain $\text{sign}[GW^{NJ} - GW^{CJ}] = \text{sign}[-\eta(R + S + T + U + W)]$. Therefore, we investigate the sign of $R+S+T+U+W$.

When $\gamma \to \infty$, we obtain $R + S + T + U + W = (\eta^2 + 24\eta + 96)(2\eta^2 + 9\eta + 9)^2\infty > 0$. This is because the degrees of $R>0$, $U>0$ and $W>0$ about γ are larger than those of $S < 0$ and $T<0$. Therefore, when γ is sufficiently large, we obtain $R + S + T + U + W > 0$ for any η.

However, when γ is sufficiently small, the sign of $R+S+T+U+W$ depends on the size of η. When $\gamma = \frac{1}{2}$, we obtain $R + S + T + U + W < 0(\geq)0$ if $\eta > (\leq)16.283$. This is because the effects of $S<0$ and $T<0$ become large when η increases. Therefore, when $\eta > 16.283$, the large γ is required to obtain $R+S+T+U+W>0$. Then, we obtain $R + S + T + U + W = (16\gamma^4 + 128\gamma^3 + 232\gamma^2 - 12\gamma - 105)\infty$ when $\eta \to \infty$. Therefore, when $\eta \to \infty$, we obtain $R + S + T + U + W \geq (<)0$ when $\gamma \geq (<)0.597$. As a result, when $\gamma \geq 0.597$, we obtain $R + S + T + U + W \geq 0$ for any η.

On the other hand, when η decreases, the effects of $S<0$ and $T<0$ become small. When $\eta = 0$, we obtain $R+S+T+U+W>0$ ($R = 31104\gamma^4 > 0$ and $S=T=U=W=0$) for any γ. Therefore, when η is small, especially, when $\eta \leq 16.283$, the signs of $R>0$, $U>0$ and $W>0$ dominate those of $S<0$ and $T<0$, and we obtain $R + S + T + U + W \geq 0$ for any $\gamma \geq \frac{1}{2}$.

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Finally, when $\eta > 16.283$ and $\frac{1}{2} \leq \gamma < 0.597$, we obtain $\gamma_{GWNC}(\eta)$ such that $R+S+T+U+W=0$, and $R + S + T + U + W \leq (>)0$ when $\gamma \leq (>)\gamma_{GWNC}$. In addition, when η increases, because the effects of $S<0$ and $T<0$ become large, the large γ is required to obtain $R+S+T+U+W>0$. Therefore, we obtain $\partial\gamma_{GWNC}/\partial\eta > 0$ as depicted in figure 5.

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