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Summary

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Keywords: Environmental Research Joint Venture, Environmental R&D, Time-consistent Emission Tax, Competition Policy, Cournot Duopoly

JEL Classification: O32, L13, Q55, Q58

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Environmental research joint ventures and time-consistent emission tax*

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Abstract

This paper presents an examination of the socially efficient formation of environmental R&D in Cournot duopoly in a setting where a regulator has no precommitment ability for an emission tax. The results reveal that if the environmental damage is slight, alternatively, given severe environmental damage and large inefficiency in environmental R&D costs, then environmental research joint venture (ERJV) cartelization is socially efficient. However, if environmental damage is severe, and if a firm's R&D costs are limited, then, in stark contrast to results of previous studies, environmental R&D competition is socially more efficient than the other three scenarios (i.e., environmental R&D cartelization, ERJV competition, and ERJV cartelization), although R&D competition is the case of "NO information sharing and NO R&D coordination."

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1 Introduction

Innovation is strongly encouraged by both competition and cooperation among firms with market power. It should be regarded as a part of the design of a competition policy. The truth is that research joint ventures (RJVs) used to be taboo in US competition policy until the US government enacted the National Cooperative Research Act (NCRA) in 1984.[1] However, in 1961 the Japanese government enacted the Act on Mining and Manufacturing Industry Technology Research Association on the model of research association system in the UK.[2] This law increased the number of RJVs formed in Japan. At that time, Japanese firms were poor compared to those of other economically developed countries. For that reason, the Japanese government recommended that firms form RJVs. As a consequence, the shortage of funds yielded a strategic promotion of RJV. Forming a RJV is now regarded as a firm's usual strategy to survive market competition.[3] In the competition policies of many developed countries, RJVs are allowable subject to a *rule of reason* rather than being illegal *per se*.[4]

In the field of economics of environmental regulation, several studies have been undertaken to reveal better R&D formation to internalize environmental externalities with a highly advanced emission abatement technology or to improve environmental quality (e.g., Chiou and Hu (2001), Poyago-Theotoky (2007, 2010), and Yakita and Yamauchi (2011)).[5] However, clear-cut and comprehensive policy maps of socially efficient R&D formations corresponding to various regulatory circumstances are not still provided. With respect to forming a RJV, Grossman and Shapiro (1986, Section 4) point out that two conflicting effects exists: social benefits and anticompetitive dangers. Furthermore, in the field of law and policy, it has been considered that RJV should be evaluated from the perspective of a *rule of reason*. Nevertheless, investigations and discussions of RJV for emissions reduction are utterly inadequate. Unfortunately, evaluation under a *rule of reason* lags far behind real-world environmental innovation. Therefore, the question persists: under what circumstances is RJV in an environmental area socially justified? This question has not been answered. This paper presents an examination of the question of whether environmental research joint venture (ERJV) formations within a symmetric R&D/Cournot model improve social welfare.

To investigate that question analytically, following the well-known definition of R&D scenarios by Kamien *et al.* (1992, p.1295), we introduce two ERJV formation scenarios—ERJV competition and ERJV cartelization—into a setting where a regulator has no precommitment ability for an emission tax (i.e., time-consistent emission tax)[see Table 1]. In the cases of such ERJV formations, both firms must agree to share environmental R&D findings completely before the R&D stage. The difference between ERJV competition and ERJV cartelization lies in the absence or presence of coordination of each firm's R&D effort level in the R&D stage.

In this article, to examine the welfare performance of ERJV, we compare these ERJV for-

[1] The primary aim of the NCRA was to relax US antitrust law.

[2] For details of this Japanese case, see Nakamura *et al.* (1997) and Sakakibara and Cho (2002).

[3] For details of economic studies of RJV, see Katsoutacos and Ulph (1998), Amir (2000a), Cassiman (2000), Kline (2000), Vilasuso and Frascatore (2000), Caloghirou *et al.*(2003), Leahy and Neary (2005), Atallah (2007), Socorro (2007), and others.

[4] For details related to a *rule of reason*, see Areeda (1986).

[5] As some representative studies of environmental R&D from the empirical side, for example, see Scott (2003, 2005).

mations' equilibrium outcomes with the equilibrium outcomes of environmental R&D competition/cartelization explored by Poyago-Theotoky (2007). Examinations conducted by Poyago-Theotoky (2007) did not consider a possibility of endogenous ERJV formations. Therefore, the technological spillover effect is invariably given exogenously in her model: firms can not control it. However, we include two options of endogenous ERJV formation in which firms can set the technological spillover effect at the full level from the initial given level, only if both firms agree on full information sharing of environmental R&D findings before the R&D stage.[6] This study compares the four scenarios defined in Table 1.

Table 1: Four scenarios.[7]

Scenarios	R&D stage	Production stage (after R&D stage)
Environmental R&D competition (case N)	Firms compete. Each firm decides its own environmental R&D investment level to maximize its own profit given R&D investments of the rival.	Firms compete (under emission tax policy). Emissions are reduced by the firm's environmental R&D investment and some spillover effects from rivals' fruits of R&D activity.
Environmental R&D cartelization (case C)	Each firm coordinates its own environmental R&D investment level to maximize joint profits.	Firms compete (under emission tax policy). Emissions are reduced by the firm's environmental R&D investment and some spillover effects from rivals' fruits of R&D activity.
ERJV competition (case NJ)	Firms agree to form an ERJV to avoid duplication of R&D activities. Firms fully share the fruits of environmental R&D. The degree of technological spillover is perfect. However, each firm chooses its own R&D investment level non-cooperatively to maximize its own profit.	Firms compete (under emission tax policy). Emissions are reduced by the sum of all environmental R&D efforts in the industry.
ERJV cartelization (case CJ)	Firms agree to form an ERJV to avoid duplication of R&D activities. Firms fully share the fruits of environmental R&D. The degree of technological spillover is perfect. Firms coordinate their R&D investment level to maximize joint profits.	Firms compete (under emission tax policy). Emissions are reduced by the sum of all environmental R&D efforts in the industry.

In the context of policy design in an oligopolistic market, strategic interactions exist between the government and firms with market power. In the absence of a precommitment ability related to the emission tax rate, firms' environmental R&D investment can affect the government's future decision-making for emission tax policy. Strictly speaking, polluting firms can have some incentives for large environmental R&D investment to elicit a lower emission tax rate from the government. The effect is designated as a *ratchet effect*.[8] The problems of timing and precommitment ability in environmental policy has been explored widely (Abrego and Perroni (2002), Requate (2005), and Brunner *et al.*(2012)), but little attention has been devoted to the

[6]For examples of related literature related to endogenous spillover model in the context of cost-reducing R&D, see Katsoutacos and Ulph (1998) and Gersbach and Schmutzler (2003).

[7]This table follows Kamien *et al.* (1992, Table 1).

[8]For details of discussions about a *ratchet effect*, see Hepburn (2006, Section 5), Puller (2006), and Brunner *et al.*(2012, Section 3.1.3).

welfare performance of ERJV in the presence of *ratchet effect*. The primary purpose of this study is to clarify that point, which remains obscure.

Our main contributions are the following. First, we demonstrate that both firms will invariably form ERJV cartelization within a symmetric R&D/Cournot model to the extent that the government approves completely R&D coordination and full information sharing under the time-consistent emission tax. Neither ERJV competition nor environmental R&D competition/cartelization is formed spontaneously in this context. Second, although we confirm that the welfare performance of ERJV cartelization always dominates ERJV competition and environmental R&D cartelization, we also demonstrate, in sharp contrast to results of previous works, that ERJV cartelization is not necessarily socially efficient or acceptable. The welfare performance of ERJV cartelization varies with conditions of three exogenous parameters: environmental damage, cost efficiency of R&D investment, and the initial technological spillover effect. We identify the conditions in which environmental R&D competition is socially more efficient than ERJV cartelization. In other words, this article reveals the border of policy change between environmental R&D competition and ERJV cartelization. We provide complete examinations of ERJV formations under time-consistent emission tax and theoretical foundations for ERJV policy and firms' behaviors.

This paper is presented as follows. The next section introduces the model and some preliminary points related to the evaluation of ERJV. The third section is an exploration of the firm profitability under ERJV. The fourth section presents an examination of which R&D regime has social superiority; then it presents a derivation of theoretical contributions and policy implications. The final section presents conclusions.

2 The model and some preliminary points

First, Section 2.1 presents the model to investigate the welfare performance of ERJV.[9] Second, as some preliminary points related to the derivation of new findings, Section 2.2 provides equilibrium outcomes under four scenarios defined in Table 1.

2.1 The model

This paper assumes an industry comprising two homogeneous firms (firm i and firm j) engaging in a quantity competition with the same cost structure and emissions-reducing technology. Then q_i denotes firm i's output. Demand is given as $p(q_i, q_j) = a - (q_i + q_j),\ (i, j = 1, 2;\ i \neq j)$, where $a(> 0)$ is a market size parameter.

The value of each firm's emissions per unit output is one. Firm i's environmental R&D effort is captured by z_i. Both firms use end-of-pipe technology for pollution abatement. Although this technology is insufficient for reducing emissions per unit output, it mitigates emissions by adsorbing pollution at the end of the production process. Flue gas desulfurization equipment and activated carbon adsorption equipment are examples of end-of-pipe technology.

Firm i receives benefits not only from its own environmental R&D effort but also from the effort of its rival. When firm i's production level is q_i, then the R&D expenditure $(\gamma/2)z_i^2, (\gamma > 0)$

[9] Whereas the current model fundamentally follows the Poyago-Theotoky (2007) model, the setting of this article includes the Poyago-Theotoky model for subgames. See also the footnote 12.

enables firm i to abate its emissions from q_i to $e_i(q_i, z_i) \equiv q_i - z_i - \beta z_j$. A lower value of γ implies higher efficiency of the R&D cost. Symmetric parameter $\beta \in [0, 1]$ denotes spillover effects of environmental R&D. Firm i's positive externalities from a rival's R&D effort are captured by βz_j. No fixed costs for pollution abatement are necessary.[10] In addition, firm i's total cost function is additively separable with respect to production costs and R&D expenditures: $C(q_i, z_i) = cq_i + (\gamma/2)z_i^2, (c > 0, A \equiv a - c > 0)$.

Firm i's net emissions $e_i(q_i, z_i)$ depend on both the output and environmental R&D effort. Total emissions $E \equiv \sum_{i=1}^{2} e_i(q_i, z_i)$ cause environmental damage $D(E) \equiv dE^2/2$; $d(> \underline{d} \equiv (-1 + \sqrt{3})/2)$ is the damage coefficient.[11] Social welfare SW is defined as the sum of consumers' surplus and the producer's surplus less environmental damage $D(E)$ and total R&D expenditures, $\sum_{i=1}^{2}(\gamma/2)z_i^2$.

When an ERJV is formed between two firms, full information sharing is conducted. Therefore, in the case of ERJV, the value of spillover parameter, β, is endogenously set as $\beta = 1$ by each firm. This article assumes that no fixed costs for ERJV are necessary.

In this model, the government has policy instruments of two types. One is competition policy: a combination of ERJV policy and approval/disapproval of R&D coordination. At the first stage, the government decides according to a *rule of reason* whether an ERJV is socially prohibited, and also whether R&D coordination is socially allowable. The other role is emission tax policy. This study assumes that the government has no precommitment ability for an emission tax rate t. The tax rate is determined to maximize social welfare after firms' environmental R&D investment at stage 2. The time structure is the following.[12]

<u>Stage 1</u>: The government decides whether an ERJV between two firms is socially prohibited, and also whether R&D coordination is socially allowable.

<u>Stage 2</u>: When ERJV is allowable, firms choose whether they form an ERJV.

<u>Stage 3</u>: Firms determine whether they behave in environmental R&D activities cooperatively or non-cooperatively. Furthermore, each firm also chooses its environmental R&D effort level.

<u>Stage 4</u>: The regulator determines the emission tax rate to maximize social welfare.

<u>Stage 5</u>: Firm i determines its output level non-cooperatively to maximize its own profit.

2.2 Equilibrium outcomes

The solution concept used here is the subgame-perfect Nash equilibrium (SPNE). The five-stage game explained above is solved by backward induction. This subsection presents the examinations of subgames: stages 3, 4, and 5. A brief sketch of solution procedures under four scenarios defined in Table 1 and results are as follows.

[10] Most existing incumbents in the chemical products industry have installed emissions-reducing equipment of end-of-pipe type. Such firms' investments in quality-improvement of desulfurization catalyst and hydrodenitrogenation catalyst are applicable to this model because no fixed set-up cost for abatement is required. In contrast to the current model, the installation of a new pollution abatement technology incurs a fixed set-up cost. As an example of the model including such a fixed set-up cost, see Requate and Unold (2003).

[11] An interior solution for environmental R&D is guaranteed by the following assumption: $d > \underline{d} \equiv (-1+\sqrt{3})/2$. For details, see Ouchida and Goto (2011).

[12] Stages 3, 4, and 5 in this paper are identical to the three-stage game developed by Poyago-Theotoky (2007). Stages 1 and 2 are newly added for the analyses described in this paper.

2.2.1 Environmental R&D competition

In this case, neither firm forms an ERJV or coordinates R&D effort level. In the last stage, firm i's profit is

$$\pi_i(q_i, q_j) = \{a - (q_i + q_j)\}q_i - cq_i - t\{q_i - z_i - \beta z_j\} - (\gamma/2)z_i^2.$$

Each firm decides its own output level non-cooperatively and simultaneously. From the first-order conditions for profit maximization, the symmetric equilibrium output is derived as $q(t) = (A - t)/3$.

Consequently, social welfare in Stage 4 is calculated as

$$SW(t) = 2Aq(t) - 2[q(t)]^2 - (d/2)\{2q(t) - (1+\beta)\{z_i + z_j\}\}^2 - \sum_{i=1}^{2}(\gamma/2)z_i^2.$$

The regulator determines the emission tax rate to maximize social welfare. From the first-order condition for social welfare maximization, the subgame equilibrium tax rate is obtained as

$$t(z_i, z_j) = \frac{(2d-1)A - 3d(1+\beta)\{z_i + z_j\}}{2(1+d)}. \tag{1}$$

Therefore, firm i's profit during the third stage is

$$\pi_i(z_i, z_j) = [q(t(z_i, z_j))]^2 + t(z_i, z_j)\{z_i + \beta z_j\} - (\gamma/2)z_i^2.$$

Each firm non-cooperatively and simultaneously determines its environmental R&D effort. The first-order conditions for profit maximization, $\partial\pi_i(z_i, z_j)/\partial z_i = 0,\ (i, j = 1, 2; i \neq j)$, generate the following equilibrium R&D efforts.[13]

$$z_{\mathrm{N}} = \frac{[(1+d)(2d-1) + d(1+\beta)]A}{2\gamma(1+d)^2 + d(1+\beta)[3(3+\beta) + d(7+\beta)]}.$$

The equilibrium levels of the emission tax rate, output level for each firm, profit, and social welfare are presented in Table 2.

2.2.2 Environmental R&D cartelization

Solution procedures of stages 4 and 5 are identical to those in Section 2.2.1. However, environmental R&D cartelization implies that two firms do not form an ERJV, but they cooperatively and simultaneously determine their environmental R&D effort to maximize joint profits, $\pi_i(z_i, z_j) + \pi_j(z_i, z_j)$, during the third stage. Then, the equilibrium levels of the equilibrium outcomes are derived in Table 2.[14]

[13] Subscript "N" stands for the case of environmental R&D competition. This paper follows the scheme employed by Kamien *et al.* (1992).

[14] Subscript "C" denotes the case of environmental R&D cartelization.

2.2.3 ERJV competition

In this case, both firms form an ERJV to avoid duplication of R&D activities and share all R&D information, but they do not coordinate the R&D effort level. When the ERJV is formed, firms can control the degree of technological spillover. Full sharing of the fruits of R&D is characterized by $\beta = 1$, although the value of β is exogenous in the previous two cases. The equilibrium outcomes under ERJV competition are produced from the equilibrium values of environmental R&D competition case after setting $\beta = 1$. The results are presented in Table 2.[15]

2.2.4 ERJV cartelization

In this case, both firms form an ERJV to avoid duplication of R&D activities. They coordinate the R&D effort level to maximize joint profits during the third stage. In addition, sharing of the fruits of R&D is fully conducted. As in the case of ERJV competition, firms can control the degree of spillover effect and set $\beta = 1$. The equilibrium outcomes under ERJV cartelization are derived from the equilibrium values of environmental R&D cartelization case after setting $\beta = 1$. Results are calculated in Table 2.[16]

3 Firm profitability under ERJV

It is possible to analyze firms' behavior at stage 2. ERJV is not implemented without more profitability rather than any other scenario. This section presents an examination of whether ERJV yields for each firm more profitability. With regard to private incentive of R&D cooperation, Poyago-Theotoky (2007, p.70) shows that $\pi_{\mathrm{C}} > \pi_{\mathrm{N}}$.[17] That study straightforwardly demonstrates that $\pi_{\mathrm{CJ}} > \pi_{\mathrm{NJ}}$ when $\beta = 1$. Consequently, ERJV competition is not implemented.

Comparing the equilibrium profit under ERJV cartelization, π_{CJ}, with that under environmental R&D cartelization, π_{C}, engenders the following proposition.

Proposition 1. $\pi_{\mathrm{CJ}} \geq \pi_{\mathrm{C}} > \pi_{\mathrm{N}}$ *for all* $d > \underline{d}$, $\gamma > 0$ *and* $\beta \in [0, 1]$.

Proof: See Appendix A. □

The investigations above state that ERJV cartelization between symmetric Cournot duopolists always yields the greatest profitability among four scenarios. Therefore, both firms invariably carry out ERJV cartelization at stage 2 unless it is prohibited. The intuitive explanation here is that, under ERJV cartelization, each firm can avoid R&D competition and enjoy the highest free-rider effect and joint-profit maximization effect.

In the literature related to cost-reducing R&D, papers by Atallah (2005a, 2005b), Lambertini and Rossini (2009) and others reveal RJV cartelization as privately beneficial for each firm. Proposition 1 signifies that, irrespective of the difference of the theoretical framework between the emission-reducing R&D model and the cost-reducing R&D model, there exist some private incentives for RJV cartelization.

[15] Subscript "NJ" stands for the case of ERJV competition.
[16] Subscript "CJ" stands for the case of ERJV cartelization.
[17] See Appendix A.

Table 2: Equilibrium outcomes under four scenarios.

	Environmental R&D competition	Environmental R&D cartelization
Environmental R&D efforts	$z_{\mathrm{N}} = \dfrac{[(1+d)(2d-1)+d(1+\beta)]A}{2\gamma(1+d)^2+d(1+\beta)[3(3+\beta)+d(7+\beta)]}$	$z_{\mathrm{C}} = \dfrac{(1+\beta)[(1+d)(2d-1)+2d]A}{2\gamma(1+d)^2+4d(3+2d)(1+\beta)^2}$
Emission tax rate	$t_{\mathrm{N}} = \dfrac{[d(2d-3)(1+\beta)^2+2\gamma(2d^2+d-1)]A}{4\gamma(1+d)^2+2d(1+\beta)[3(3+\beta)+d(7+\beta)]}$	$t_{\mathrm{C}} = \dfrac{[d(2d-3)(1+\beta)^2+\gamma(2d^2+d-1)]A}{2\gamma(1+d)^2+4d(3+2d)(1+\beta)^2}$
Output level	$q_{\mathrm{N}} = \dfrac{[2(1+d)\gamma+d(1+\beta)(7+4d+3\beta)]A}{4\gamma(1+d)^2+2d(1+\beta)[3(3+\beta)+d(7+\beta)]}$	$q_{\mathrm{C}} = \dfrac{[d(5+2d)(1+\beta)^2+\gamma(1+d)]A}{2\gamma(1+d)^2+4d(3+2d)(1+\beta)^2}$
Profits	$\pi_{\mathrm{N}} = q_{\mathrm{N}}^2+t_{\mathrm{N}}(1+\beta)z_{\mathrm{N}}-(\gamma/2)z_{\mathrm{N}}^2$	$\pi_{\mathrm{C}} = q_{\mathrm{C}}^2+t_{\mathrm{C}}(1+\beta)z_{\mathrm{C}}-(\gamma/2)z_{\mathrm{C}}^2$
Social welfare	$SW_{\mathrm{N}} = 2Aq_{\mathrm{N}}-2q_{\mathrm{N}}^2-2d\{q_{\mathrm{N}}-(1+\beta)z_{\mathrm{N}}\}^2-\gamma z_{\mathrm{N}}^2$	$SW_{\mathrm{C}} = 2Aq_{\mathrm{C}}-2q_{\mathrm{C}}^2-2d\{q_{\mathrm{C}}-(1+\beta)z_{\mathrm{C}}\}^2-\gamma z_{\mathrm{C}}^2$

	ERJV competition	ERJV cartelization
Environmental R&D efforts	$z_{\mathrm{NJ}} = \dfrac{(2d^2+3d-1)A}{2\gamma(1+d)^2+8d(3+2d)}$	$z_{\mathrm{CJ}} = \dfrac{(2d^2+3d-1)A}{\gamma(1+d)^2+8d(3+2d)}$
Emission tax rate	$t_{\mathrm{NJ}} = \dfrac{[2d(2d-3)+\gamma(2d^2+d-1)]A}{2\gamma(1+d)^2+8d(3+2d)}$	$t_{\mathrm{CJ}} = \dfrac{[4d(2d-3)+\gamma(2d^2+d-1)]A}{2\gamma(1+d)^2+16d(3+2d)}$
Output level	$q_{\mathrm{NJ}} = \dfrac{[(1+d)\gamma+2d(5+2d)]A}{2\gamma(1+d)^2+8d(3+2d)}$	$q_{\mathrm{CJ}} = \dfrac{[4d(5+2d)+\gamma(1+d)]A}{2\gamma(1+d)^2+16d(3+2d)}$
Profits	$\pi_{\mathrm{NJ}} = q_{\mathrm{NJ}}^2+2t_{\mathrm{NJ}}z_{\mathrm{NJ}}-(\gamma/2)z_{\mathrm{NJ}}^2$	$\pi_{\mathrm{CJ}} = q_{\mathrm{CJ}}^2+2t_{\mathrm{CJ}}z_{\mathrm{CJ}}-(\gamma/2)z_{\mathrm{CJ}}^2$
Social welfare	$SW_{\mathrm{NJ}} = 2Aq_{\mathrm{NJ}}-2q_{\mathrm{NJ}}^2-2d\{q_{\mathrm{NJ}}-2z_{\mathrm{NJ}}\}^2-\gamma z_{\mathrm{NJ}}^2$	$SW_{\mathrm{CJ}} = 2Aq_{\mathrm{CJ}}-2q_{\mathrm{CJ}}^2-2d\{q_{\mathrm{CJ}}-2z_{\mathrm{CJ}}\}^2-\gamma z_{\mathrm{CJ}}^2$

4 R&D regimes and social superiority

Next we explore the government's decision-making at stage 1. With respect to the equilibrium social welfare presented in Table 2, from Poyago-Theotoky's (2007) investigation, it can be understood that $SW_{\text{CJ}} > SW_{\text{NJ}}$.[18] Therefore, the equilibrium social welfare under ERJV cartelization dominates that under ERJV competition. Hereinafter, we do not analyze the case of ERJV competition. Instead, we concentrate on the welfare performance of the other R&D regimes. This section presents an examination of whether equilibrium social welfare under ERJV cartelization dominates that under the other two R&D scenarios: environmental R&D competition and environmental R&D cartelization.

4.1 Environmental R&D cartelization versus ERJV cartelization

Comparing equilibrium social welfare under environmental R&D cartelization, SW_{C}, with that under ERJV cartelization, SW_{CJ}, engenders the following proposition.

Proposition 2. *$SW_{\text{CJ}} \geq SW_{\text{C}}$ for all $d > \underline{d}$, $\gamma > 0$ and $\beta \in [0, 1]$.*

Proof: See Appendix B. □

This proposition states that, in terms of social-welfare maximization, ERJV cartelization invariably dominates the case of environmental R&D cartelization. Full information sharing generates welfare superiority compared with the case of R&D cartelization. This result is consistent with our intuition.

4.2 Environmental R&D competition versus ERJV cartelization

We now compare the two equilibrium social welfare levels. The difference between SW_{CJ} and SW_{N} is given as shown below.

$$SW_{\text{CJ}} - SW_{\text{N}} = \frac{J(d, \gamma; \beta)A^2}{[\Delta^{\beta=1}]^2\Gamma^2} \gtreqless 0. \tag{2}$$

Appendix C presents details of Equation (2). Figure 1 presents a graphical analysis of this comparison. First, with respect to welfare ranking of each region in Figure 1, we confirm the following results. In the region above (below) the curve γ_φ in Figure 1, $SW_{\text{C}} \geq (<) SW_{\text{N}}$ and $z_{\text{C}} \geq (<) z_{\text{N}}$.[19] In addition, when the degree of spillover is perfect (i.e., $\beta = 1$), then $SW_{\text{CJ}} > SW_{\text{NJ}}$.

Next, let us specifically examine the case of imperfect spillover (i.e., $\beta \neq 1$). Then, as new findings, the following are apparent. When $\underline{d} < d \leq 3/2$, then $J(d, \gamma; \beta) \geq 0$; i.e., ERJV

[18] See Equation (14), Corollary 1 and Proof of Proposition 2 in Appendix A in Poyago-Theotoky (2007). In her analysis, ERJVs are not examined as the central question. Strictly speaking, she shows that $SW_{\text{C}}|_{\beta=1} > SW_{\text{N}}|_{\beta=1}$ in the special case in which the value of exogenous parameter β is one.

[19] The definition of φ is given by Poyago-Theotoky (2007, p.69). The definition of γ_φ is $\gamma_\varphi \equiv \{\gamma > 0 | \varphi \equiv d(3-2d)(1+\beta)^2(1-\beta) + 2\gamma(2d^2\beta + 2d\beta - \beta + d) = 0, d > 3/2\}$. The curve γ_φ in Figure 1 is identical to the borderline in Figure 1 of Poyago-Theotoky (2007, p.71). The curve γ_φ has the following property: $\lim_{d\to+\infty} \gamma_\varphi = (1+\beta)^2(1-\beta)/2\beta$. Therefore, when $\beta = 1$, then γ_φ disappears. Her investigation reveals that $\text{sign}\{\varphi\} = \text{sign}\{z_{\text{C}} - z_{\text{N}}\} = \text{sign}\{SW_{\text{C}} - SW_{\text{N}}\}$.

cartelization is invariably socially superior to environmental R&D competition, irrespective of the value of γ. However, if $d > 3/2$, then ERJV cartelization is superior (inferior) to environmental R&D competition for all $\gamma \geq (<) \gamma_{JV} \equiv \{\gamma(>0) | J(d, \gamma; \beta) = 0, d > 3/2\}$.[20] In the region above (below) the curve γ_{JV} in Figure 1, $SW_{\mathrm{CJ}} \geq (<) SW_{\mathrm{N}}$. These results are summarized as Proposition 3.

Proposition 3. *Presuming that $\beta < 1$, new findings are described below.*
(i) If $\underline{d} < d \leq 3/2$, then $SW_{\mathrm{CJ}} \geq SW_{\mathrm{N}}$ for all $\gamma > 0$ and $\beta \in [0, 1)$.
(ii) If $d > 3/2$ and $\gamma \geq \gamma_{JV}$, then $SW_{\mathrm{CJ}} \geq SW_{\mathrm{N}}$ for all $\beta \in [0, 1)$.
(iii) If $d > 3/2$ and $\gamma < \gamma_{JV}$, then $SW_{\mathrm{CJ}} < SW_{\mathrm{N}}$ for all $\beta \in [0, 1)$.

Poyago-Theotoky (2010) points out that negative emission taxes (emissions subsidies) might be socially justified. When the value of d is in the interval $(\underline{d}, 3/2)$, and also the value of γ is strictly smaller than the critical value $\gamma^t_{\mathrm{CJ}} \equiv 4d(3 - 2d)/(2d^2 + d - 1)$, then the regulator can mitigate market inefficiency through emissions subsidies and ERJV cartelization irrespective of the value of the spillover parameter.[21] In fact, in Region I below the curve γ^t_{CJ} in Figure 1, we can observe that $t_{\mathrm{CJ}} < 0$ and $SW_{\mathrm{CJ}} > SW_{\mathrm{C}} > SW_{\mathrm{N}}$.[22] Propositions 2 and 3 show that, even in the case of ERJV cartelization, not only its desirability but also a negative emission tax (emissions subsidy) might still be socially justified. However, only when $\gamma < \gamma^t_{\mathrm{N}} (< \gamma^t_{\mathrm{CJ}})$, then $t_{\mathrm{N}} < 0$.[23] Therefore, in Region IV below the curve γ_{JV}, the value of t_{N} is always positive. In Figure 1, Regions II and III respectively denote the region between γ^t_{CJ} and γ_φ, and the region between γ_φ and γ_{JV}. Whereas Poyago-Theotoky (2007) shows that γ_φ represents the borderline of $\mathrm{sign}\{SW_{\mathrm{C}} - SW_{\mathrm{N}}\}$, the existence of γ_{JV}, which plays key roles in Proposition 3, is newly revealed by this research. As Figure 1 clarifies, when $\beta = 1$, then Regions III and IV disappear.[24]

Table 3 presents the welfare ranking and the sign of an emission tax rate in each region of Figure 1. Figure 1 and Table 3 show that, in Regions I, II, and III, the implementation of ERJV cartelization yields an improvement in social welfare. However, particularly addressing the existence of Region IV, it seems clear that ERJV cartelization is not necessarily better than any other scenario. Particularly with a small value of γ, $(\gamma < \gamma_{JV})$, and a large value of d, $(d > 3/2)$, environmental R&D competition is socially efficient. In other words, part (iii) of Proposition 3 shows that ERJV cartelization is socially harmful in Region IV. Therefore, it is apparent that a social incentive for ERJV cartelization does not always exist. Additionally, it is important to compare the cost-reducing R&D literature with our result to enrich the theoretical argument in relation to competition policy in environmental innovation area. The welfare ranking in Region IV is inconsistent with the findings of d'Aspremont and Jacquemin (1988, 1990), Atallah (2005a) and Lambertini and Rossini (2009) and others, who show the social superiority of RJV

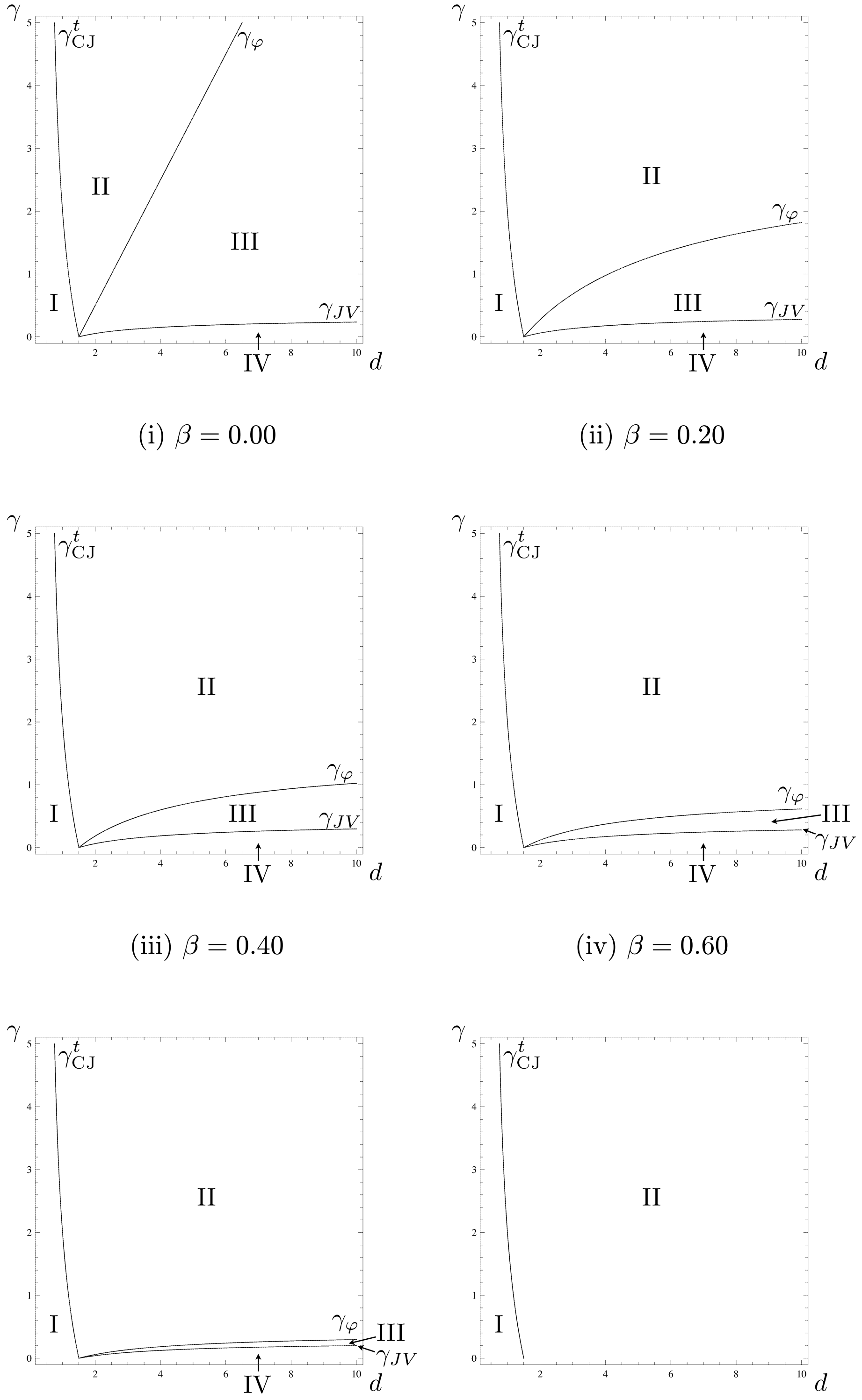
[20] It is straightforward to verify the existence and uniqueness of γ_{JV}. However, it is extremely difficult to obtain γ_{JV} explicitly by solving the cubic equation $J(d, \gamma; \beta) = 0$.

[21] The critical value $\gamma^t_{\mathrm{CJ}} \equiv 4d(3 - 2d)/(2d^2 + d - 1)$ is derived from $t_{\mathrm{CJ}} = 0$.

[22] Our companion paper (Ouchida and Goto (2014)) reveals the emission-reducing effects of negative emission taxes (i.e., emission subsidies). That study is very closely related to the investigations conducted by this paper. For details, see Proposition 2 and Figure 1(iv) in Ouchida and Goto (2014).

[23] The critical value $\gamma^t_{\mathrm{N}} \equiv d(3 - 2d)(1 + \beta)^2/2(2d^2 + d - 1)$ is derived from $t_{\mathrm{N}} = 0$.

[24] See Appendix C and footnote 19 in this paper.



(i) $\beta = 0.00$ (ii) $\beta = 0.20$

(iii) $\beta = 0.40$ (iv) $\beta = 0.60$

(v) $\beta = 0.80$ (vi) $\beta = 1.00$

Figure 1. Environmental R&D competition versus ERJV cartelization.

cartelization.[25] Moreover, the result of Proposition 3(iii) differs greatly from the result of typical textbook (Belleflamme and Peitz (2010, pp.498-499)), demonstrating that RJV cartelization yields a socially superior performance to that obtained through non-cooperative R&D.

Table 3. Welfare ranking and the sign of the emission tax rate.

Region	Emission tax	Welfare ranking
I	$t_{\mathrm{CJ}} < 0$	$SW_{\mathrm{CJ}} > SW_{\mathrm{C}} > SW_{\mathrm{N}}$
II	$t_{\mathrm{CJ}} > 0$	$SW_{\mathrm{CJ}} > SW_{\mathrm{C}} > SW_{\mathrm{N}}$
III	$t_{\mathrm{CJ}} > 0$	$SW_{\mathrm{CJ}} > SW_{\mathrm{N}} > SW_{\mathrm{C}}$
IV	$t_{\mathrm{N}} > 0$	$SW_{\mathrm{N}} > SW_{\mathrm{CJ}} > SW_{\mathrm{C}}$

The reason for the existence of Region IV can be interpreted as follows. Greater R&D efforts decrease the emission tax rate determined during the second stage.[26] In studies by Hepburn (2006), Puller (2006), and Brunner *et al.*(2012), this decrease is designated as a "*ratchet effect.*" If the value of γ is small, then the joint-profit maximization effect is dominated by the profit-enhancing effect through the *ratchet effect.* For that reason, there can exist circumstances such that $z_{\mathrm{CJ}} < z_{\mathrm{N}}$.[27] Greater environmental R&D efforts increase production levels and consumer surplus. When the damage is severe and when R&D costs are highly efficient, greater R&D efforts generated through R&D competition results in a large increase effect on consumer surplus and a large mitigating effect on environmental damage. These effects dominate the increasing effect of R&D costs. Therefore, the equilibrium social welfare under environmental R&D competition is greater than in the case of ERJV cartelization. However, when the damage coefficient is small ($d < 3/2$), the equilibrium social welfare under environmental R&D competition is dominated by that under ERJV cartelization because of the small mitigating effect of environmental damage.

4.3 Theoretical contributions

In this article, two theoretical findings are newly provided by the modelling of a firm's endogenous choice of ERJV. Each firm can endogenously set the value of technological spillover as $\beta = 1$, only if both firms agree to form an ERJV at stage 2. That game-theoretic setting of ERJV enables us to evaluate the welfare performance of four scenarios (in Table 1): environmental R&D competition, environmental R&D cartelization, ERJV competition, and ERJV cartelization.

[25] Atallah (2005a) examines the case of asymmetric spillover. His analysis includes results of the case of symmetric perfect spillover. Therefore, it is easy to ascertain the social superiority of RJV cartelization under symmetrically perfect spillover. For details, see Figure 7 of Atallah (2005a, p.933). In addition, for details of the well-known R&D models by d'Aspremont and Jacquemin (1988, 1990) and Kamien *et al.* (1992), see reports by Amir (2000b) and Amir *et al.* (2003). Furthermore, in the literature related to cost-reducing innovation, some works reveal that industry-wide RJV cartelization is not necessarily socially efficient. As examples, see Yin (1999), Amir (2000a), and Yun *et al.* (2000). The models constructed in those studies differ from the model presented here.

[26] See, Equation (1). In fact, one obtains that $\partial t(z_i, z_j)/\partial z_i < 0$.

[27] A comparison between z_{CJ} and z_{N} yields the following result: $z_{\mathrm{CJ}} \geq (<) z_{\mathrm{N}}$ for all $\gamma \geq (<) \hat{\gamma}_{\mathrm{N}} \equiv d(1-\beta)\delta/\mu$, where $\mu \equiv (1+d)^2[2d^2 + (4-\beta)d - 1](> 0)$ and $\delta \equiv 18d^3 + 41d^2 + 12d - 15 + \beta(d+3)(d^2+3d-1)(> 0)$. Therefore, if the value of γ is small ($\gamma < \hat{\gamma}_{\mathrm{N}}$), then $z_{\mathrm{CJ}} < z_{\mathrm{N}}$. This result differs from the result reported by d'Aspremont and Jacquemin (1988, 1990), which showed that cost-reducing R&D efforts under RJV cartelization are invariably greater than under any other scenario. In addition, this result implies that the case of ERJV cartelization does not always yield larger investments than under any other scenario presented in Table 1.

The first finding is that each firm invariably has a private incentive for ERJV cartelization (Proposition 1). However, the second finding is that ERJV cartelization does not necessarily lead to social efficiency (Propositions 2 and 3). More precisely, in Regions I, II, and III in Figure 1, ERJV cartelization is socially beneficial and feasible. However, in Region IV, firms can not receive both profits under ERJV competition/cartelization ($\pi_{\rm NJ}$ and $\pi_{\rm CJ}$) because the welfare-maximizing regulator can accommodate neither information sharing nor R&D coordination, whereas firms prefer ERJV cartelization.

These findings justify that the stages of ERJV policy and firm's decision on ERJV are invariably required. In other words, the indispensability of examinations of stages 1 and 2 in the present model is proved by the results of Propositions 2 and 3, although the Poyago-Theotoky model is missing both stages even though there invariably exist firms' private incentives for ERJV cartelization. Instead, this article presents development of the five-stage game by adding stages of ERJV policy (stage 1) and firm's decisions on ERJV (stage 2) to the Poyago-Theotoky's three-stage model, and also provides complete examinations. Therefore, this paper provides theoretical foundations of ERJV policy and firms' behavior under a time-consistent emission tax.

4.4 Policy implications

Policy implications derived from results of our theoretical analysis must be considered. This paper presents the possibility of the superiority of ERJV cartelization. In Regions I, II, and III shown in Figure 1, no intervention for ERJV cartelization is necessary. However, in stark contrast to the well-known result of cost-reducing R&D, we infer that environmental R&D competition is socially efficient when pollution abatement is highly cost-efficient ($\gamma < \gamma_{JV}$), and also when environmental damage is severe ($d > 3/2$).[28] In Region IV in Figure 1, the government should allow neither information sharing nor R&D coordination.

The category of pollution abatement technology in this model is called "end-of-pipe." Measures of this category achieve reduction of the amount of emissions by absorption at the end of production processes. Flue gas desulfurization equipment and activated carbon adsorption equipment are examples of this type. As an example of the oligopolistic market corresponding to this model, we can mention oil refinery firms and firms with huge chemical plants.[29] In fact, such oligopolistic firms use end-of-pipe technology and also invest in R&D for quality improvement of catalysts. The results presented in the present paper provide important policy implications related to whether ERJV cartelization in a horizontal relation is allowed socially.

[28] As described in this paper, the value of d is assumed as an exogenous damage parameter. Strictly speaking, however, the value of d should be derived from the scientific findings of environmental epidemiology and public health. Therefore, more interdisciplinary studies must be conducted to produce effective ERJV guidelines.

[29] In Japan, 20 major firms involved in petroleum and chemical industries established the "Research Association of Refinery Integration for Group-Operation (RING)" in May 2000. For details, see RING's website (URL: http://www.ring.or.jp/). The main purpose of RING is to encourage RJV projects for cost-effective plant operation and emissions reduction among participants to enhance a competitive advantage and to survive in the international market. Particularly with respect to RING's ERJV projects, the striking characteristic is that the research consortia consist of firms belonging to different industries. Apparently, the participating firms have intentionally avoided a horizontal ERJV to avoid exposure to prosecution for violation of antitrust laws. Is a horizontal ERJV socially harmful, or beneficial? At least the Japanese antitrust authorities have not earnestly considered the question. Other such countries might exist. The results presented in this paper are important and indispensable for the design of a practical competition policy for ERJV.

5 Concluding remarks

This article presents an analytical framework of ERJV in Cournot duopoly. As described in Section 2, we explicitly introduce ERJV formations with the following condition. Each firm can endogenously choose the perfect information-sharing of technological knowledge, only if both firms agree to form an ERJV. Under the setup, this paper evaluates the welfare performance of ERJV.

Our analysis obtains the following facts and policy implications. If environmental damage is large, and if the parameter of environmental R&D cost is small enough, then environmental R&D competition is socially efficient. It is particularly interesting that our analysis reveals the social superiority of environmental R&D competition, although that scenario is the case of "NO information sharing and NO R&D coordination." Under such circumstances, the antitrust authorities should disallow not only ERJV cartelization but also environmental R&D cartelization. This result is fairly counterintuitive and differs from the well-known conclusions reported in the existing literature. However, if environmental damage is small, alternatively if there is severe environmental damage and high inefficiency of environmental R&D costs, then ERJV cartelization is socially efficient. Under those circumstances, firms should be allowed to form an ERJV cartelization. Such cooperative behavior yields improved social welfare. Furthermore, each firm invariably has a private incentive for ERJV cartelization. Our results can considerably enrich future RJV studies in environmental innovation areas, although only a few ERJV studies have been made heretofore.

In the last two decades, although the importance of environmental R&D has been increasingly socially recognized, a few studies have examined the welfare performance of ERJV.[30] To design appropriate environmental R&D policy, detailed and practical policy suggestions on ERJV are desired by policymakers of many countries.[31] As an example, the Japanese antitrust guidelines for RJV (Japan Fair Trade Commission [JFTC] (1993) and its amended versions) are ambiguous and frail.[32] Unfortunately, the Japanese antitrust authorities (JFTC) have formed detailed policy guidelines for ERJV only to a slight degree. This fact signifies that the Japanese antitrust authorities' discretionary power on ERJV is too strong. Under such regulatory circumstances, the ERJV participants might be faced with the risk of becoming a noncompliant (or administratively sanctioned) firm involuntarily because the rules are not enacted definitely. In addition, the lack of detailed rules might generate a disincentive to forming an ERJV. This

[30] For example, see Katsoulacos *et al.* (2001) and McDonald and Poyago-Theotoky (2012). Chiou and Hu (2001) examined environmental R&D formations under precommitment of an emission tax. McDonald and Poyago-Theotoky (2012) and Poyago-Theotoky (2007, footnote 2) presented important explanations about the misleading analysis conducted by Chiou and Hu (2001).

[31] The EU's antitrust guidelines for the horizontal cooperation agreements are "Guidelines on the applicability of Article 101 of the Treaty on the Functioning of the European Union to horizontal co-operation agreements." These appear on the European Commission's website (URL: http://ec.europa.eu/competition/antitrust/legislation/horizontal.html). Regarding the US guidelines for JV, the Federal Trade Commission (FTC) and the U.S. Department of Justice (DOJ) issued "Antitrust Guidelines for Collaborations Among Competitors" on the FTC's website (URL: http://www.ftc.gov/os/2000/04/ftcdojguidelines.pdf). Caloghirou *et al.* (2003), Caloghirou *et al.* (2004) and Motta (2004, Chapters 1 and 4) reported historical, legal, and economic explanations for RJV. Grossman and Shapiro (1986) provided important arguments related to RJV and antitrust guidelines. These studies are useful for understanding the antitrust policies of influential countries and regions.

[32] For details, see the website of JFTC (URL: http://www.jftc.go.jp/en/).

research provides theoretical findings to improve such weak points.

Some directions for future research are described below. First, the case of an asymmetric spillover parameter must be analyzed in line with Atallah's (2005a, 2005b, 2007) examinations. Second, it is necessary to explore the case of price competition in a differentiated duopoly. Third, it is important to examine environmental R&D cooperation in a vertical relation.

Appendix A

Proof of Proposition 1: Differentiation between π_{CJ} and π_{C} is given as

$$\pi_{\mathrm{CJ}} - \pi_{\mathrm{C}} = \frac{2\gamma(1-\beta)BA^2}{\Delta^2[\Delta^{\beta=1}]^2} \geq 0, \tag{3}$$

where $B \equiv [2d^2+3d-1]^2[8d(3+2d)+\gamma(1+d)^2][2d(2d+3)(1+\beta)^2+\gamma(1+d)^2] > 0$, $\Delta \equiv 2\gamma(1+d)^2+4d(3+2d)(1+\beta)^2 > 0$, and $\Delta^{\beta=1} \equiv 2\gamma(1+d)^2+16d(3+2d) > 0$. Only when $\beta = 1$, then $\pi_{\mathrm{CJ}} = \pi_{\mathrm{C}}$.

Poyago-Theotoky (2007) proves that $\pi_{\mathrm{C}} > \pi_{\mathrm{N}}$. In fact, from Equation (16) in Poyago-Theotoky (2007, p.70),

$$\pi_{\mathrm{C}} - \pi_{\mathrm{N}} = \frac{A^2(1+d)^2\kappa^2}{4\Delta^2\Gamma^2} > 0, \tag{4}$$

where $\kappa \equiv d(3-2d)(1-\beta)(1+\beta)^2+2\gamma[d+\beta(2d^2+2d-1)]$ and $\Gamma \equiv 2\gamma(1+d)^2+d(1+\beta)[3(3+\beta)+d(7+\beta)] > 0$.

Equations (3) and (4) show that each firm invariably has some private incentives for ERJV cartelization. Therefore, we have that $\pi_{\mathrm{CJ}} \geq \pi_{\mathrm{C}} > \pi_{\mathrm{N}}$ for all $d > \underline{d}$, $\gamma > 0$ and $\beta \in [0,1]$. □

Appendix B

Proof of Proposition 2: After some manipulation, the difference between SW_{CJ} and SW_{C} is derived as

$$SW_{\mathrm{CJ}} - SW_{\mathrm{C}} = \frac{4(1-\beta)(3+\beta)LA^2}{[\Delta^{\beta=1}]^2\Delta^2} \geq 0,$$

where

$$\begin{aligned} L \equiv\ & 32d^3(3+2d)^2(5+2d)(1+\beta)^2+8d^2(3+2d)[4(1+d)(3+2d) \\ & +(1+\beta)^2(48d^5+216d^4+292d^3+76d^2-51d+5)]\gamma \\ & +2d(1+d)^2[64d^5+446d^3+155d^2-64d+3 \\ & +(1+\beta)^2(2d^2+3d-1)(8d^3+26d^2+21d+1)]\gamma^2 \\ & +(1+d)^4(2d^2+3d-1)(2d^2+5d+1)\gamma^3 > 0. \end{aligned}$$

$\Delta(>0)$ and $\Delta^{\beta=1}(>0)$ are both defined in Appendix A. Therefore, we have $SW_{\mathrm{CJ}} \geq SW_{\mathrm{C}}$ for all $d > \underline{d}$, $\gamma > 0$ and $\beta \in [0,1]$. □

Appendix C

Welfare comparison: We obtain the following result.

$$SW_{\rm CJ} - SW_{\rm N} = \frac{J(d,\gamma;\beta)A^2}{[\Delta^{\beta=1}]^2\Gamma^2} \gtreqless 0$$

Therein,

$$\begin{aligned}
J(d,\gamma;\beta) &\equiv y + 8\gamma[k_0 + k_1\gamma + k_2\gamma^2], \\
y &\equiv -64d^3(1-\beta)(1+\beta)^2(1+d)^2(2d-3)[21+51d+26d^2 \\
&\quad +\beta(3+13d+6d^2)] \gtreqless 0, \\
\lambda_3 &\equiv 32d^5 + 201d^4 + 324d^3 + 154d^2 - 12d + 9 > 0, \\
\lambda_2 &\equiv 768d^5 + 2457d^4 + 2924d^3 + 994d^2 - 180d + 81 > 0, \\
\lambda_1 &\equiv 2720d^5 + 7735d^4 + 8172d^3 + 2278d^2 - 452d + 279 > 0, \\
\lambda_0 &\equiv 1216d^5 + 2023d^4 + 132d^3 - 1666d^2 - 156d + 687 > 0, \\
k_0 &\equiv d^2\{(1-\beta)[4(1+\beta)[16(3+\beta) + (1+\beta)(1-\beta)]d^6 + \lambda_3\beta^3 + \lambda_2\beta^2 \\
&\quad +\lambda_1\beta + \lambda_0] + 128(1+d)^2(2d+1)(2d+3)(2d^2+3d-1)\} > 0, \\
k_1 &\equiv 2d(1+d)^2\{(1-\beta)[d^2(d+1)(d+2)\beta^3 + d(1+d)(2d^3+14d^2 \\
&\quad +16d-1)\beta^2 + d(8d^4+101d^3+200d^2+91d-19)\beta + 94d^5 \\
&\quad +406d^4+499d^3+72d^2-112d+5\beta+27] \\
&\quad +4[20d^5+144d^4+170d^3+50d^2-2d-9]\} > 0, \\
k_2 &\equiv (1+d)^4\{(1-\beta)[8d^2+4(5+\beta)d+7+3\beta]d^2 \\
&\quad +4d^4+4d^3+d^2+2(4+\beta)d-3\} > 0.
\end{aligned}$$

In addition, $\Delta^{\beta=1}(>0)$ and $\Gamma(>0)$ are both defined in Appendix A. It is straightforward to verify the sign of each of the definitions presented above.

If $\underline{d} < d \leq 3/2$, then $y \geq 0$ for all $\beta \in [0,1)$. Therefore, when $\underline{d} < d \leq 3/2$, then $J(d,\gamma;\beta) \geq 0$; i.e., $SW_{\rm CJ} \geq SW_{\rm N}$ irrespective of the value of γ. However, when $d > 3/2$, then $y < 0$ for all $\beta \in [0,1)$. Therefore, when $d > 3/2$, then the sign of $J(d,\gamma;\beta)$ is indeterminate. As portrayed in Figure 1, $SW_{\rm CJ} \geq (<) SW_{\rm N}$ for all $\gamma \geq (<) \gamma_{JV} \equiv \{\gamma(>0) | J(d,\gamma;\beta) = 0, d > 3/2\}$. From the definition of $J(d,\gamma;\beta)$, verifying the existence and uniqueness of γ_{JV} is straightforward.

Furthermore, assuming that $d > 3/2$, only when $\beta = 1$, we have $y = 0$; i.e., $SW_{\rm CJ} > SW_{\rm NJ}$. This observation readily implies that there invariably exists some Region IV unless $\beta = 1$.

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Environmental research joint ventures and time-consistent emission tax*

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Abstract

This paper presents an examination of the socially efficient formation of environmental R&D in Cournot duopoly in a setting where a regulator has no precommitment ability for an emission tax. The results reveal that if the environmental damage is slight, alternatively, given severe environmental damage and large inefficiency in environmental R&D costs, then environmental research joint venture (ERJV) cartelization is socially efficient. However, if environmental damage is severe, and if a firm's R&D costs are limited, then, in stark contrast to results of previous studies, environmental R&D competition is socially more efficient than the other three scenarios (i.e., environmental R&D cartelization, ERJV competition, and ERJV cartelization), although R&D competition is the case of "NO information sharing and NO R&D coordination."

JEL Classification: O32; L13; Q55; Q58.

Keywords: Environmental research joint venture; Environmental R&D; Time-consistent emission tax; Competition policy; Cournot duopoly

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1 Introduction

Innovation is strongly encouraged by both competition and cooperation among firms with market power. It should be regarded as a part of the design of a competition policy. The truth is that research joint ventures (RJVs) used to be taboo in US competition policy until the US government enacted the National Cooperative Research Act (NCRA) in 1984.[1] However, in 1961 the Japanese government enacted the Act on Mining and Manufacturing Industry Technology Research Association on the model of research association system in the UK.[2] This law increased the number of RJVs formed in Japan. At that time, Japanese firms were poor compared to those of other economically developed countries. For that reason, the Japanese government recommended that firms form RJVs. As a consequence, the shortage of funds yielded a strategic promotion of RJV. Forming a RJV is now regarded as a firm's usual strategy to survive market competition.[3] In the competition policies of many developed countries, RJVs are allowable subject to a *rule of reason* rather than being illegal *per se*.[4]

In the field of economics of environmental regulation, several studies have been undertaken to reveal better R&D formation to internalize environmental externalities with a highly advanced emission abatement technology or to improve environmental quality (e.g., Chiou and Hu (2001), Poyago-Theotoky (2007, 2010), and Yakita and Yamauchi (2011)).[5] However, clear-cut and comprehensive policy maps of socially efficient R&D formations corresponding to various regulatory circumstances are not still provided. With respect to forming a RJV, Grossman and Shapiro (1986, Section 4) point out that two conflicting effects exists: social benefits and anticompetitive dangers. Furthermore, in the field of law and policy, it has been considered that RJV should be evaluated from the perspective of a *rule of reason*. Nevertheless, investigations and discussions of RJV for emissions reduction are utterly inadequate. Unfortunately, evaluation under a *rule of reason* lags far behind real-world environmental innovation. Therefore, the question persists: under what circumstances is RJV in an environmental area socially justified? This question has not been answered. This paper presents an examination of the question of whether environmental research joint venture (ERJV) formations within a symmetric R&D/Cournot model improve social welfare.

To investigate that question analytically, following the well-known definition of R&D scenarios by Kamien *et al.* (1992, p.1295), we introduce two ERJV formation scenarios—ERJV competition and ERJV cartelization—into a setting where a regulator has no precommitment ability for an emission tax (i.e., time-consistent emission tax)[see Table 1]. In the cases of such ERJV formations, both firms must agree to share environmental R&D findings completely before the R&D stage. The difference between ERJV competition and ERJV cartelization lies in the absence or presence of coordination of each firm's R&D effort level in the R&D stage.

In this article, to examine the welfare performance of ERJV, we compare these ERJV for-

[1] The primary aim of the NCRA was to relax US antitrust law.

[2] For details of this Japanese case, see Nakamura *et al.* (1997) and Sakakibara and Cho (2002).

[3] For details of economic studies of RJV, see Katsoutacos and Ulph (1998), Amir (2000a), Cassiman (2000), Kline (2000), Vilasuso and Frascatore (2000), Caloghirou *et al.*(2003), Leahy and Neary (2005), Atallah (2007), Socorro (2007), and others.

[4] For details related to a *rule of reason*, see Areeda (1986).

[5] As some representative studies of environmental R&D from the empirical side, for example, see Scott (2003, 2005).

mations' equilibrium outcomes with the equilibrium outcomes of environmental R&D competition/cartelization explored by Poyago-Theotoky (2007). Examinations conducted by Poyago-Theotoky (2007) did not consider a possibility of endogenous ERJV formations. Therefore, the technological spillover effect is invariably given exogenously in her model: firms can not control it. However, we include two options of endogenous ERJV formation in which firms can set the technological spillover effect at the full level from the initial given level, only if both firms agree on full information sharing of environmental R&D findings before the R&D stage.[6] This study compares the four scenarios defined in Table 1.

Table 1: Four scenarios.[7]

Scenarios	R&D stage	Production stage (after R&D stage)
Environmental R&D competition (case N)	Firms compete. Each firm decides its own environmental R&D investment level to maximize its own profit given R&D investments of the rival.	Firms compete (under emission tax policy). Emissions are reduced by the firm's environmental R&D investment and some spillover effects from rivals' fruits of R&D activity.
Environmental R&D cartelization (case C)	Each firm coordinates its own environmental R&D investment level to maximize joint profits.	Firms compete (under emission tax policy). Emissions are reduced by the firm's environmental R&D investment and some spillover effects from rivals' fruits of R&D activity.
ERJV competition (case NJ)	Firms agree to form an ERJV to avoid duplication of R&D activities. Firms fully share the fruits of environmental R&D. The degree of technological spillover is perfect. However, each firm chooses its own R&D investment level non-cooperatively to maximize its own profit.	Firms compete (under emission tax policy). Emissions are reduced by the sum of all environmental R&D efforts in the industry.
ERJV cartelization (case CJ)	Firms agree to form an ERJV to avoid duplication of R&D activities. Firms fully share the fruits of environmental R&D. The degree of technological spillover is perfect. Firms coordinate their R&D investment level to maximize joint profits.	Firms compete (under emission tax policy). Emissions are reduced by the sum of all environmental R&D efforts in the industry.

In the context of policy design in an oligopolistic market, strategic interactions exist between the government and firms with market power. In the absence of a precommitment ability related to the emission tax rate, firms' environmental R&D investment can affect the government's future decision-making for emission tax policy. Strictly speaking, polluting firms can have some incentives for large environmental R&D investment to elicit a lower emission tax rate from the government. The effect is designated as a *ratchet effect*.[8] The problems of timing and precommitment ability in environmental policy has been explored widely (Abrego and Perroni (2002), Requate (2005), and Brunner *et al.*(2012)), but little attention has been devoted to the

[6]For examples of related literature related to endogenous spillover model in the context of cost-reducing R&D, see Katsoutacos and Ulph (1998) and Gersbach and Schmutzler (2003).

[7]This table follows Kamien *et al.* (1992, Table 1).

[8]For details of discussions about a *ratchet effect*, see Hepburn (2006, Section 5), Puller (2006), and Brunner *et al.*(2012, Section 3.1.3).

welfare performance of ERJV in the presence of *ratchet effect*. The primary purpose of this study is to clarify that point, which remains obscure.

Our main contributions are the following. First, we demonstrate that both firms will invariably form ERJV cartelization within a symmetric R&D/Cournot model to the extent that the government approves completely R&D coordination and full information sharing under the time-consistent emission tax. Neither ERJV competition nor environmental R&D competition/cartelization is formed spontaneously in this context. Second, although we confirm that the welfare performance of ERJV cartelization always dominates ERJV competition and environmental R&D cartelization, we also demonstrate, in sharp contrast to results of previous works, that ERJV cartelization is not necessarily socially efficient or acceptable. The welfare performance of ERJV cartelization varies with conditions of three exogenous parameters: environmental damage, cost efficiency of R&D investment, and the initial technological spillover effect. We identify the conditions in which environmental R&D competition is socially more efficient than ERJV cartelization. In other words, this article reveals the border of policy change between environmental R&D competition and ERJV cartelization. We provide complete examinations of ERJV formations under time-consistent emission tax and theoretical foundations for ERJV policy and firms' behaviors.

This paper is presented as follows. The next section introduces the model and some preliminary points related to the evaluation of ERJV. The third section is an exploration of the firm profitability under ERJV. The fourth section presents an examination of which R&D regime has social superiority; then it presents a derivation of theoretical contributions and policy implications. The final section presents conclusions.

2 The model and some preliminary points

First, Section 2.1 presents the model to investigate the welfare performance of ERJV.[9] Second, as some preliminary points related to the derivation of new findings, Section 2.2 provides equilibrium outcomes under four scenarios defined in Table 1.

2.1 The model

This paper assumes an industry comprising two homogeneous firms (firm i and firm j) engaging in a quantity competition with the same cost structure and emissions-reducing technology. Then q_i denotes firm i's output. Demand is given as $p(q_i, q_j) = a - (q_i + q_j),\ (i, j = 1, 2;\ i \neq j)$, where $a(> 0)$ is a market size parameter.

The value of each firm's emissions per unit output is one. Firm i's environmental R&D effort is captured by z_i. Both firms use end-of-pipe technology for pollution abatement. Although this technology is insufficient for reducing emissions per unit output, it mitigates emissions by adsorbing pollution at the end of the production process. Flue gas desulfurization equipment and activated carbon adsorption equipment are examples of end-of-pipe technology.

Firm i receives benefits not only from its own environmental R&D effort but also from the effort of its rival. When firm i's production level is q_i, then the R&D expenditure $(\gamma/2)z_i^2, (\gamma > 0)$

[9] Whereas the current model fundamentally follows the Poyago-Theotoky (2007) model, the setting of this article includes the Poyago-Theotoky model for subgames. See also the footnote 12.

enables firm i to abate its emissions from q_i to $e_i(q_i, z_i) \equiv q_i - z_i - \beta z_j$. A lower value of γ implies higher efficiency of the R&D cost. Symmetric parameter $\beta \in [0, 1]$ denotes spillover effects of environmental R&D. Firm i's positive externalities from a rival's R&D effort are captured by βz_j. No fixed costs for pollution abatement are necessary.[10] In addition, firm i's total cost function is additively separable with respect to production costs and R&D expenditures: $C(q_i, z_i) = cq_i + (\gamma/2)z_i^2, (c > 0, A \equiv a - c > 0)$.

Firm i's net emissions $e_i(q_i, z_i)$ depend on both the output and environmental R&D effort. Total emissions $E \equiv \sum_{i=1}^{2} e_i(q_i, z_i)$ cause environmental damage $D(E) \equiv dE^2/2$; $d(> \underline{d} \equiv (-1 + \sqrt{3})/2)$ is the damage coefficient.[11] Social welfare SW is defined as the sum of consumers' surplus and the producer's surplus less environmental damage $D(E)$ and total R&D expenditures, $\sum_{i=1}^{2}(\gamma/2)z_i^2$.

When an ERJV is formed between two firms, full information sharing is conducted. Therefore, in the case of ERJV, the value of spillover parameter, β, is endogenously set as $\beta = 1$ by each firm. This article assumes that no fixed costs for ERJV are necessary.

In this model, the government has policy instruments of two types. One is competition policy: a combination of ERJV policy and approval/disapproval of R&D coordination. At the first stage, the government decides according to a *rule of reason* whether an ERJV is socially prohibited, and also whether R&D coordination is socially allowable. The other role is emission tax policy. This study assumes that the government has no precommitment ability for an emission tax rate t. The tax rate is determined to maximize social welfare after firms' environmental R&D investment at stage 2. The time structure is the following.[12]

- Stage 1: The government decides whether an ERJV between two firms is socially prohibited, and also whether R&D coordination is socially allowable.
- Stage 2: When ERJV is allowable, firms choose whether they form an ERJV.
- Stage 3: Firms determine whether they behave in environmental R&D activities cooperatively or non-cooperatively. Furthermore, each firm also chooses its environmental R&D effort level.
- Stage 4: The regulator determines the emission tax rate to maximize social welfare.
- Stage 5: Firm i determines its output level non-cooperatively to maximize its own profit.

2.2 Equilibrium outcomes

The solution concept used here is the subgame-perfect Nash equilibrium (SPNE). The five-stage game explained above is solved by backward induction. This subsection presents the examinations of subgames: stages 3, 4, and 5. A brief sketch of solution procedures under four scenarios defined in Table 1 and results are as follows.

[10]Most existing incumbents in the chemical products industry have installed emissions-reducing equipment of end-of-pipe type. Such firms' investments in quality-improvement of desulfurization catalyst and hydrodenitrogenation catalyst are applicable to this model because no fixed set-up cost for abatement is required. In contrast to the current model, the installation of a new pollution abatement technology incurs a fixed set-up cost. As an example of the model including such a fixed set-up cost, see Requate and Unold (2003).

[11]An interior solution for environmental R&D is guaranteed by the following assumption: $d > \underline{d} \equiv (-1+\sqrt{3})/2$. For details, see Ouchida and Goto (2011).

[12]Stages 3, 4, and 5 in this paper are identical to the three-stage game developed by Poyago-Theotoky (2007). Stages 1 and 2 are newly added for the analyses described in this paper.

2.2.1 Environmental R&D competition

In this case, neither firm forms an ERJV or coordinates R&D effort level. In the last stage, firm i's profit is

$$\pi_i(q_i, q_j) = \{a - (q_i + q_j)\}q_i - cq_i - t\{q_i - z_i - \beta z_j\} - (\gamma/2)z_i^2.$$

Each firm decides its own output level non-cooperatively and simultaneously. From the first-order conditions for profit maximization, the symmetric equilibrium output is derived as $q(t) = (A - t)/3$.

Consequently, social welfare in Stage 4 is calculated as

$$SW(t) = 2Aq(t) - 2[q(t)]^2 - (d/2)\{2q(t) - (1+\beta)\{z_i + z_j\}\}^2 - \sum_{i=1}^{2}(\gamma/2)z_i^2.$$

The regulator determines the emission tax rate to maximize social welfare. From the first-order condition for social welfare maximization, the subgame equilibrium tax rate is obtained as

$$t(z_i, z_j) = \frac{(2d-1)A - 3d(1+\beta)\{z_i + z_j\}}{2(1+d)}. \tag{1}$$

Therefore, firm i's profit during the third stage is

$$\pi_i(z_i, z_j) = [q(t(z_i, z_j))]^2 + t(z_i, z_j)\{z_i + \beta z_j\} - (\gamma/2)z_i^2.$$

Each firm non-cooperatively and simultaneously determines its environmental R&D effort. The first-order conditions for profit maximization, $\partial\pi_i(z_i, z_j)/\partial z_i = 0,\ (i, j = 1, 2; i \neq j)$, generate the following equilibrium R&D efforts.[13]

$$z_{\mathrm{N}} = \frac{[(1+d)(2d-1) + d(1+\beta)]A}{2\gamma(1+d)^2 + d(1+\beta)[3(3+\beta) + d(7+\beta)]}.$$

The equilibrium levels of the emission tax rate, output level for each firm, profit, and social welfare are presented in Table 2.

2.2.2 Environmental R&D cartelization

Solution procedures of stages 4 and 5 are identical to those in Section 2.2.1. However, environmental R&D cartelization implies that two firms do not form an ERJV, but they cooperatively and simultaneously determine their environmental R&D effort to maximize joint profits, $\pi_i(z_i, z_j) + \pi_j(z_i, z_j)$, during the third stage. Then, the equilibrium levels of the equilibrium outcomes are derived in Table 2.[14]

[13] Subscript "N" stands for the case of environmental R&D competition. This paper follows the scheme employed by Kamien *et al.* (1992).

[14] Subscript "C" denotes the case of environmental R&D cartelization.

2.2.3 ERJV competition

In this case, both firms form an ERJV to avoid duplication of R&D activities and share all R&D information, but they do not coordinate the R&D effort level. When the ERJV is formed, firms can control the degree of technological spillover. Full sharing of the fruits of R&D is characterized by $\beta = 1$, although the value of β is exogenous in the previous two cases. The equilibrium outcomes under ERJV competition are produced from the equilibrium values of environmental R&D competition case after setting $\beta = 1$. The results are presented in Table 2.[15]

2.2.4 ERJV cartelization

In this case, both firms form an ERJV to avoid duplication of R&D activities. They coordinate the R&D effort level to maximize joint profits during the third stage. In addition, sharing of the fruits of R&D is fully conducted. As in the case of ERJV competition, firms can control the degree of spillover effect and set $\beta = 1$. The equilibrium outcomes under ERJV cartelization are derived from the equilibrium values of environmental R&D cartelization case after setting $\beta = 1$. Results are calculated in Table 2.[16]

3 Firm profitability under ERJV

It is possible to analyze firms' behavior at stage 2. ERJV is not implemented without more profitability rather than any other scenario. This section presents an examination of whether ERJV yields for each firm more profitability. With regard to private incentive of R&D cooperation, Poyago-Theotoky (2007, p.70) shows that $\pi_{\mathrm{C}} > \pi_{\mathrm{N}}$.[17] That study straightforwardly demonstrates that $\pi_{\mathrm{CJ}} > \pi_{\mathrm{NJ}}$ when $\beta = 1$. Consequently, ERJV competition is not implemented.

Comparing the equilibrium profit under ERJV cartelization, π_{CJ}, with that under environmental R&D cartelization, π_{C}, engenders the following proposition.

Proposition 1. $\pi_{\mathrm{CJ}} \geq \pi_{\mathrm{C}} > \pi_{\mathrm{N}}$ *for all* $d > \underline{d}$, $\gamma > 0$ *and* $\beta \in [0, 1]$.

Proof: See Appendix A. □

The investigations above state that ERJV cartelization between symmetric Cournot duopolists always yields the greatest profitability among four scenarios. Therefore, both firms invariably carry out ERJV cartelization at stage 2 unless it is prohibited. The intuitive explanation here is that, under ERJV cartelization, each firm can avoid R&D competition and enjoy the highest free-rider effect and joint-profit maximization effect.

In the literature related to cost-reducing R&D, papers by Atallah (2005a, 2005b), Lambertini and Rossini (2009) and others reveal RJV cartelization as privately beneficial for each firm. Proposition 1 signifies that, irrespective of the difference of the theoretical framework between the emission-reducing R&D model and the cost-reducing R&D model, there exist some private incentives for RJV cartelization.

[15] Subscript "NJ" stands for the case of ERJV competition.
[16] Subscript "CJ" stands for the case of ERJV cartelization.
[17] See Appendix A.

Table 2: Equilibrium outcomes under four scenarios.

	Environmental R&D competition	Environmental R&D cartelization
Environmental R&D efforts	$z_{\mathrm{N}} = \frac{[(1+d)(2d-1)+d(1+\beta)]A}{2\gamma(1+d)^2+d(1+\beta)[3(3+\beta)+d(7+\beta)]}$	$z_{\mathrm{C}} = \frac{(1+\beta)[(1+d)(2d-1)+2d]A}{2\gamma(1+d)^2+4d(3+2d)(1+\beta)^2}$
Emission tax rate	$t_{\mathrm{N}} = \frac{[d(2d-3)(1+\beta)^2+2\gamma(2d^2+d-1)]A}{4\gamma(1+d)^2+2d(1+\beta)[3(3+\beta)+d(7+\beta)]}$	$t_{\mathrm{C}} = \frac{[d(2d-3)(1+\beta)^2+\gamma(2d^2+d-1)]A}{2\gamma(1+d)^2+4d(3+2d)(1+\beta)^2}$
Output level	$q_{\mathrm{N}} = \frac{[2(1+d)\gamma+d(1+\beta)(7+4d+3\beta)]A}{4\gamma(1+d)^2+2d(1+\beta)[3(3+\beta)+d(7+\beta)]}$	$q_{\mathrm{C}} = \frac{[d(5+2d)(1+\beta)^2+\gamma(1+d)]A}{2\gamma(1+d)^2+4d(3+2d)(1+\beta)^2}$
Profits	$\pi_{\mathrm{N}} = q_{\mathrm{N}}^2 + t_{\mathrm{N}}(1+\beta)z_{\mathrm{N}} - (\gamma/2)z_{\mathrm{N}}^2$	$\pi_{\mathrm{C}} = q_{\mathrm{C}}^2 + t_{\mathrm{C}}(1+\beta)z_{\mathrm{C}} - (\gamma/2)z_{\mathrm{C}}^2$
Social welfare	$SW_{\mathrm{N}} = 2Aq_{\mathrm{N}} - 2q_{\mathrm{N}}^2 - 2d\{q_{\mathrm{N}} - (1+\beta)z_{\mathrm{N}}\}^2 - \gamma z_{\mathrm{N}}^2$	$SW_{\mathrm{C}} = 2Aq_{\mathrm{C}} - 2q_{\mathrm{C}}^2 - 2d\{q_{\mathrm{C}} - (1+\beta)z_{\mathrm{C}}\}^2 - \gamma z_{\mathrm{C}}^2$

	ERJV competition	ERJV cartelization
Environmental R&D efforts	$z_{\mathrm{NJ}} = \frac{(2d^2+3d-1)A}{2\gamma(1+d)^2+8d(3+2d)}$	$z_{\mathrm{CJ}} = \frac{(2d^2+3d-1)A}{\gamma(1+d)^2+8d(3+2d)}$
Emission tax rate	$t_{\mathrm{NJ}} = \frac{[2d(2d-3)+\gamma(2d^2+d-1)]A}{2\gamma(1+d)^2+8d(3+2d)}$	$t_{\mathrm{CJ}} = \frac{[4d(2d-3)+\gamma(2d^2+d-1)]A}{2\gamma(1+d)^2+16d(3+2d)}$
Output level	$q_{\mathrm{NJ}} = \frac{[(1+d)\gamma+2d(5+2d)]A}{2\gamma(1+d)^2+8d(3+2d)}$	$q_{\mathrm{CJ}} = \frac{[4d(5+2d)+\gamma(1+d)]A}{2\gamma(1+d)^2+16d(3+2d)}$
Profits	$\pi_{\mathrm{NJ}} = q_{\mathrm{NJ}}^2 + 2t_{\mathrm{NJ}}z_{\mathrm{NJ}} - (\gamma/2)z_{\mathrm{NJ}}^2$	$\pi_{\mathrm{CJ}} = q_{\mathrm{CJ}}^2 + 2t_{\mathrm{CJ}}z_{\mathrm{CJ}} - (\gamma/2)z_{\mathrm{CJ}}^2$
Social welfare	$SW_{\mathrm{NJ}} = 2Aq_{\mathrm{NJ}} - 2q_{\mathrm{NJ}}^2 - 2d\{q_{\mathrm{NJ}} - 2z_{\mathrm{NJ}}\}^2 - \gamma z_{\mathrm{NJ}}^2$	$SW_{\mathrm{CJ}} = 2Aq_{\mathrm{CJ}} - 2q_{\mathrm{CJ}}^2 - 2d\{q_{\mathrm{CJ}} - 2z_{\mathrm{CJ}}\}^2 - \gamma z_{\mathrm{CJ}}^2$

4 R&D regimes and social superiority

Next we explore the government's decision-making at stage 1. With respect to the equilibrium social welfare presented in Table 2, from Poyago-Theotoky's (2007) investigation, it can be understood that $SW_{\mathrm{CJ}} > SW_{\mathrm{NJ}}$.[18] Therefore, the equilibrium social welfare under ERJV cartelization dominates that under ERJV competition. Hereinafter, we do not analyze the case of ERJV competition. Instead, we concentrate on the welfare performance of the other R&D regimes. This section presents an examination of whether equilibrium social welfare under ERJV cartelization dominates that under the other two R&D scenarios: environmental R&D competition and environmental R&D cartelization.

4.1 Environmental R&D cartelization versus ERJV cartelization

Comparing equilibrium social welfare under environmental R&D cartelization, SW_{C}, with that under ERJV cartelization, SW_{CJ}, engenders the following proposition.

Proposition 2. *$SW_{\mathrm{CJ}} \geq SW_{\mathrm{C}}$ for all $d > \underline{d}$, $\gamma > 0$ and $\beta \in [0, 1]$.*

Proof: See Appendix B. □

This proposition states that, in terms of social-welfare maximization, ERJV cartelization invariably dominates the case of environmental R&D cartelization. Full information sharing generates welfare superiority compared with the case of R&D cartelization. This result is consistent with our intuition.

4.2 Environmental R&D competition versus ERJV cartelization

We now compare the two equilibrium social welfare levels. The difference between SW_{CJ} and SW_{N} is given as shown below.

$$SW_{\mathrm{CJ}} - SW_{\mathrm{N}} = \frac{J(d, \gamma; \beta)A^2}{[\Delta^{\beta=1}]^2 \Gamma^2} \gtreqless 0. \tag{2}$$

Appendix C presents details of Equation (2). Figure 1 presents a graphical analysis of this comparison. First, with respect to welfare ranking of each region in Figure 1, we confirm the following results. In the region above (below) the curve γ_φ in Figure 1, $SW_{\mathrm{C}} \geq (<) SW_{\mathrm{N}}$ and $z_{\mathrm{C}} \geq (<) z_{\mathrm{N}}$.[19] In addition, when the degree of spillover is perfect (i.e., $\beta = 1$), then $SW_{\mathrm{CJ}} > SW_{\mathrm{NJ}}$.

Next, let us specifically examine the case of imperfect spillover (i.e., $\beta \neq 1$). Then, as new findings, the following are apparent. When $\underline{d} < d \leq 3/2$, then $J(d, \gamma; \beta) \geq 0$; i.e., ERJV

[18] See Equation (14), Corollary 1 and Proof of Proposition 2 in Appendix A in Poyago-Theotoky (2007). In her analysis, ERJVs are not examined as the central question. Strictly speaking, she shows that $SW_{\mathrm{C}}|_{\beta=1} > SW_{\mathrm{N}}|_{\beta=1}$ in the special case in which the value of exogenous parameter β is one.

[19] The definition of φ is given by Poyago-Theotoky (2007, p.69). The definition of γ_φ is $\gamma_\varphi \equiv \{\gamma > 0 | \varphi \equiv d(3-2d)(1+\beta)^2(1-\beta) + 2\gamma(2d^2\beta + 2d\beta - \beta + d) = 0, d > 3/2\}$. The curve γ_φ in Figure 1 is identical to the borderline in Figure 1 of Poyago-Theotoky (2007, p.71). The curve γ_φ has the following property: $\lim_{d \to +\infty} \gamma_\varphi = (1+\beta)^2(1-\beta)/2\beta$. Therefore, when $\beta = 1$, then γ_φ disappears. Her investigation reveals that $\mathrm{sign}\{\varphi\} = \mathrm{sign}\{z_{\mathrm{C}} - z_{\mathrm{N}}\} = \mathrm{sign}\{SW_{\mathrm{C}} - SW_{\mathrm{N}}\}$.

cartelization is invariably socially superior to environmental R&D competition, irrespective of the value of γ. However, if $d > 3/2$, then ERJV cartelization is superior (inferior) to environmental R&D competition for all $\gamma \geq (<)\gamma_{JV} \equiv \{\gamma(>0)|J(d,\gamma;\beta) = 0, d > 3/2\}$.[20] In the region above (below) the curve γ_{JV} in Figure 1, $SW_{\mathrm{CJ}} \geq (<) SW_{\mathrm{N}}$. These results are summarized as Proposition 3.

Proposition 3. *Presuming that $\beta < 1$, new findings are described below.*
(i) If $\underline{d} < d \leq 3/2$, then $SW_{\mathrm{CJ}} \geq SW_{\mathrm{N}}$ for all $\gamma > 0$ and $\beta \in [0, 1)$.
(ii) If $d > 3/2$ and $\gamma \geq \gamma_{JV}$, then $SW_{\mathrm{CJ}} \geq SW_{\mathrm{N}}$ for all $\beta \in [0, 1)$.
(iii) If $d > 3/2$ and $\gamma < \gamma_{JV}$, then $SW_{\mathrm{CJ}} < SW_{\mathrm{N}}$ for all $\beta \in [0, 1)$.

Poyago-Theotoky (2010) points out that negative emission taxes (emissions subsidies) might be socially justified. When the value of d is in the interval $(\underline{d}, 3/2)$, and also the value of γ is strictly smaller than the critical value $\gamma^t_{\mathrm{CJ}} \equiv 4d(3-2d)/(2d^2+d-1)$, then the regulator can mitigate market inefficiency through emissions subsidies and ERJV cartelization irrespective of the value of the spillover parameter.[21] In fact, in Region I below the curve γ^t_{CJ} in Figure 1, we can observe that $t_{\mathrm{CJ}} < 0$ and $SW_{\mathrm{CJ}} > SW_{\mathrm{C}} > SW_{\mathrm{N}}$.[22] Propositions 2 and 3 show that, even in the case of ERJV cartelization, not only its desirability but also a negative emission tax (emissions subsidy) might still be socially justified. However, only when $\gamma < \gamma^t_{\mathrm{N}} (< \gamma^t_{\mathrm{CJ}})$, then $t_{\mathrm{N}} < 0$.[23] Therefore, in Region IV below the curve γ_{JV}, the value of t_{N} is always positive. In Figure 1, Regions II and III respectively denote the region between γ^t_{CJ} and γ_φ, and the region between γ_φ and γ_{JV}. Whereas Poyago-Theotoky (2007) shows that γ_φ represents the borderline of sign$\{SW_{\mathrm{C}} - SW_{\mathrm{N}}\}$, the existence of γ_{JV}, which plays key roles in Proposition 3, is newly revealed by this research. As Figure 1 clarifies, when $\beta = 1$, then Regions III and IV disappear.[24]

Table 3 presents the welfare ranking and the sign of an emission tax rate in each region of Figure 1. Figure 1 and Table 3 show that, in Regions I, II, and III, the implementation of ERJV cartelization yields an improvement in social welfare. However, particularly addressing the existence of Region IV, it seems clear that ERJV cartelization is not necessarily better than any other scenario. Particularly with a small value of γ, $(\gamma < \gamma_{JV})$, and a large value of d, $(d > 3/2)$, environmental R&D competition is socially efficient. In other words, part (iii) of Proposition 3 shows that ERJV cartelization is socially harmful in Region IV. Therefore, it is apparent that a social incentive for ERJV cartelization does not always exist. Additionally, it is important to compare the cost-reducing R&D literature with our result to enrich the theoretical argument in relation to competition policy in environmental innovation area. The welfare ranking in Region IV is inconsistent with the findings of d'Aspremont and Jacquemin (1988, 1990), Atallah (2005a) and Lambertini and Rossini (2009) and others, who show the social superiority of RJV

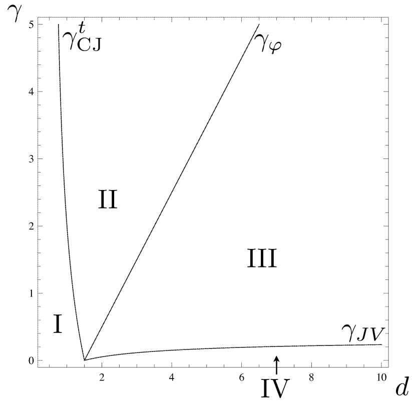
[20]It is straightforward to verify the existence and uniqueness of γ_{JV}. However, it is extremely difficult to obtain γ_{JV} explicitly by solving the cubic equation $J(d,\gamma;\beta) = 0$.

[21]The critical value $\gamma^t_{\mathrm{CJ}} \equiv 4d(3-2d)/(2d^2+d-1)$ is derived from $t_{\mathrm{CJ}} = 0$.

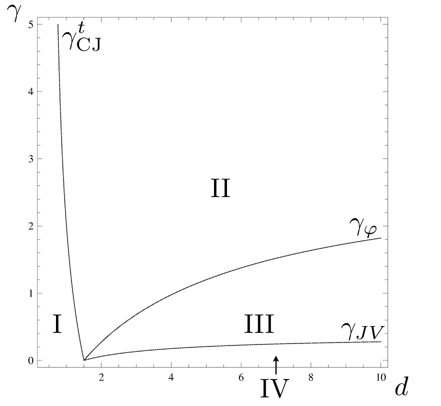
[22]Our companion paper (Ouchida and Goto (2014)) reveals the emission-reducing effects of negative emission taxes (i.e., emission subsidies). That study is very closely related to the investigations conducted by this paper. For details, see Proposition 2 and Figure 1(iv) in Ouchida and Goto (2014).

[23]The critical value $\gamma^t_{\mathrm{N}} \equiv d(3-2d)(1+\beta)^2/2(2d^2+d-1)$ is derived from $t_{\mathrm{N}} = 0$.

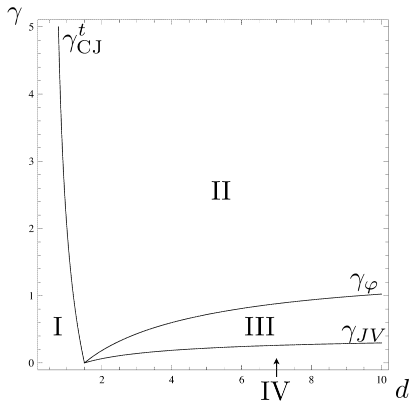
[24]See Appendix C and footnote 19 in this paper.



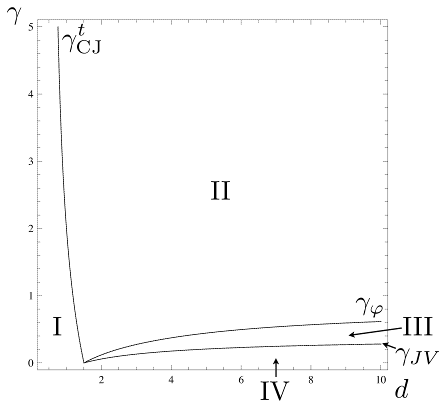
(i) $\beta = 0.00$



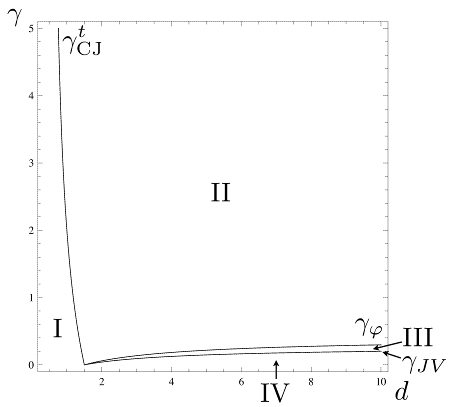
(ii) $\beta = 0.20$



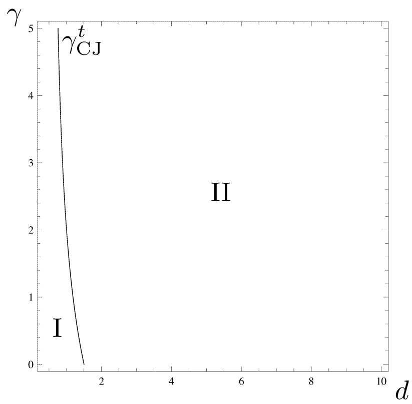
(iii) $\beta = 0.40$



(iv) $\beta = 0.60$



(v) $\beta = 0.80$



(vi) $\beta = 1.00$

Figure 1. Environmental R&D competition versus ERJV cartelization.

cartelization.[25] Moreover, the result of Proposition 3(iii) differs greatly from the result of typical textbook (Belleflamme and Peitz (2010, pp.498-499)), demonstrating that RJV cartelization yields a socially superior performance to that obtained through non-cooperative R&D.

Table 3. Welfare ranking and the sign of the emission tax rate.

Region	Emission tax	Welfare ranking
I	$t_{\mathrm{CJ}} < 0$	$SW_{\mathrm{CJ}} > SW_{\mathrm{C}} > SW_{\mathrm{N}}$
II	$t_{\mathrm{CJ}} > 0$	$SW_{\mathrm{CJ}} > SW_{\mathrm{C}} > SW_{\mathrm{N}}$
III	$t_{\mathrm{CJ}} > 0$	$SW_{\mathrm{CJ}} > SW_{\mathrm{N}} > SW_{\mathrm{C}}$
IV	$t_{\mathrm{N}} > 0$	$SW_{\mathrm{N}} > SW_{\mathrm{CJ}} > SW_{\mathrm{C}}$

The reason for the existence of Region IV can be interpreted as follows. Greater R&D efforts decrease the emission tax rate determined during the second stage.[26] In studies by Hepburn (2006), Puller (2006), and Brunner *et al.*(2012), this decrease is designated as a "*ratchet effect.*" If the value of γ is small, then the joint-profit maximization effect is dominated by the profit-enhancing effect through the *ratchet effect.* For that reason, there can exist circumstances such that $z_{\mathrm{CJ}} < z_{\mathrm{N}}$.[27] Greater environmental R&D efforts increase production levels and consumer surplus. When the damage is severe and when R&D costs are highly efficient, greater R&D efforts generated through R&D competition results in a large increase effect on consumer surplus and a large mitigating effect on environmental damage. These effects dominate the increasing effect of R&D costs. Therefore, the equilibrium social welfare under environmental R&D competition is greater than in the case of ERJV cartelization. However, when the damage coefficient is small ($d < 3/2$), the equilibrium social welfare under environmental R&D competition is dominated by that under ERJV cartelization because of the small mitigating effect of environmental damage.

4.3 Theoretical contributions

In this article, two theoretical findings are newly provided by the modelling of a firm's endogenous choice of ERJV. Each firm can endogenously set the value of technological spillover as $\beta = 1$, only if both firms agree to form an ERJV at stage 2. That game-theoretic setting of ERJV enables us to evaluate the welfare performance of four scenarios (in Table 1): environmental R&D competition, environmental R&D cartelization, ERJV competition, and ERJV cartelization.

[25] Atallah (2005a) examines the case of asymmetric spillover. His analysis includes results of the case of symmetric perfect spillover. Therefore, it is easy to ascertain the social superiority of RJV cartelization under symmetrically perfect spillover. For details, see Figure 7 of Atallah (2005a, p.933). In addition, for details of the well-known R&D models by d'Aspremont and Jacquemin (1988, 1990) and Kamien *et al.* (1992), see reports by Amir (2000b) and Amir *et al.* (2003). Furthermore, in the literature related to cost-reducing innovation, some works reveal that industry-wide RJV cartelization is not necessarily socially efficient. As examples, see Yin (1999), Amir (2000a), and Yun *et al.* (2000). The models constructed in those studies differ from the model presented here.

[26] See, Equation (1). In fact, one obtains that $\partial t(z_i, z_j)/\partial z_i < 0$.

[27] A comparison between z_{CJ} and z_{N} yields the following result: $z_{\mathrm{CJ}} \geq (<) z_{\mathrm{N}}$ for all $\gamma \geq (<) \hat{\gamma}_{\mathrm{N}} \equiv d(1-\beta)\delta/\mu$, where $\mu \equiv (1+d)^2[2d^2+(4-\beta)d-1](>0)$ and $\delta \equiv 18d^3+41d^2+12d-15+\beta(d+3)(d^2+3d-1)(>0)$. Therefore, if the value of γ is small ($\gamma < \hat{\gamma}_{\mathrm{N}}$), then $z_{\mathrm{CJ}} < z_{\mathrm{N}}$. This result differs from the result reported by d'Aspremont and Jacquemin (1988, 1990), which showed that cost-reducing R&D efforts under RJV cartelization are invariably greater than under any other scenario. In addition, this result implies that the case of ERJV cartelization does not always yield larger investments than under any other scenario presented in Table 1.

The first finding is that each firm invariably has a private incentive for ERJV cartelization (Proposition 1). However, the second finding is that ERJV cartelization does not necessarily lead to social efficiency (Propositions 2 and 3). More precisely, in Regions I, II, and III in Figure 1, ERJV cartelization is socially beneficial and feasible. However, in Region IV, firms can not receive both profits under ERJV competition/cartelization (π_{NJ} and π_{CJ}) because the welfare-maximizing regulator can accommodate neither information sharing nor R&D coordination, whereas firms prefer ERJV cartelization.

These findings justify that the stages of ERJV policy and firm's decision on ERJV are invariably required. In other words, the indispensability of examinations of stages 1 and 2 in the present model is proved by the results of Propositions 2 and 3, although the Poyago-Theotoky model is missing both stages even though there invariably exist firms' private incentives for ERJV cartelization. Instead, this article presents development of the five-stage game by adding stages of ERJV policy (stage 1) and firm's decisions on ERJV (stage 2) to the Poyago-Theotoky's three-stage model, and also provides complete examinations. Therefore, this paper provides theoretical foundations of ERJV policy and firms' behavior under a time-consistent emission tax.

4.4 Policy implications

Policy implications derived from results of our theoretical analysis must be considered. This paper presents the possibility of the superiority of ERJV cartelization. In Regions I, II, and III shown in Figure 1, no intervention for ERJV cartelization is necessary. However, in stark contrast to the well-known result of cost-reducing R&D, we infer that environmental R&D competition is socially efficient when pollution abatement is highly cost-efficient ($\gamma < \gamma_{JV}$), and also when environmental damage is severe ($d > 3/2$).[28] In Region IV in Figure 1, the government should allow neither information sharing nor R&D coordination.

The category of pollution abatement technology in this model is called "end-of-pipe." Measures of this category achieve reduction of the amount of emissions by absorption at the end of production processes. Flue gas desulfurization equipment and activated carbon adsorption equipment are examples of this type. As an example of the oligopolistic market corresponding to this model, we can mention oil refinery firms and firms with huge chemical plants.[29] In fact, such oligopolistic firms use end-of-pipe technology and also invest in R&D for quality improvement of catalysts. The results presented in the present paper provide important policy implications related to whether ERJV cartelization in a horizontal relation is allowed socially.

[28] As described in this paper, the value of d is assumed as an exogenous damage parameter. Strictly speaking, however, the value of d should be derived from the scientific findings of environmental epidemiology and public health. Therefore, more interdisciplinary studies must be conducted to produce effective ERJV guidelines.

[29] In Japan, 20 major firms involved in petroleum and chemical industries established the "Research Association of Refinery Integration for Group-Operation (RING)" in May 2000. For details, see RING's website (URL: http://www.ring.or.jp/). The main purpose of RING is to encourage RJV projects for cost-effective plant operation and emissions reduction among participants to enhance a competitive advantage and to survive in the international market. Particularly with respect to RING's ERJV projects, the striking characteristic is that the research consortia consist of firms belonging to different industries. Apparently, the participating firms have intentionally avoided a horizontal ERJV to avoid exposure to prosecution for violation of antitrust laws. Is a horizontal ERJV socially harmful, or beneficial? At least the Japanese antitrust authorities have not earnestly considered the question. Other such countries might exist. The results presented in this paper are important and indispensable for the design of a practical competition policy for ERJV.

5 Concluding remarks

This article presents an analytical framework of ERJV in Cournot duopoly. As described in Section 2, we explicitly introduce ERJV formations with the following condition. Each firm can endogenously choose the perfect information-sharing of technological knowledge, only if both firms agree to form an ERJV. Under the setup, this paper evaluates the welfare performance of ERJV.

Our analysis obtains the following facts and policy implications. If environmental damage is large, and if the parameter of environmental R&D cost is small enough, then environmental R&D competition is socially efficient. It is particularly interesting that our analysis reveals the social superiority of environmental R&D competition, although that scenario is the case of "NO information sharing and NO R&D coordination." Under such circumstances, the antitrust authorities should disallow not only ERJV cartelization but also environmental R&D cartelization. This result is fairly counterintuitive and differs from the well-known conclusions reported in the existing literature. However, if environmental damage is small, alternatively if there is severe environmental damage and high inefficiency of environmental R&D costs, then ERJV cartelization is socially efficient. Under those circumstances, firms should be allowed to form an ERJV cartelization. Such cooperative behavior yields improved social welfare. Furthermore, each firm invariably has a private incentive for ERJV cartelization. Our results can considerably enrich future RJV studies in environmental innovation areas, although only a few ERJV studies have been made heretofore.

In the last two decades, although the importance of environmental R&D has been increasingly socially recognized, a few studies have examined the welfare performance of ERJV.[30] To design appropriate environmental R&D policy, detailed and practical policy suggestions on ERJV are desired by policymakers of many countries.[31] As an example, the Japanese antitrust guidelines for RJV (Japan Fair Trade Commission [JFTC] (1993) and its amended versions) are ambiguous and frail.[32] Unfortunately, the Japanese antitrust authorities (JFTC) have formed detailed policy guidelines for ERJV only to a slight degree. This fact signifies that the Japanese antitrust authorities' discretionary power on ERJV is too strong. Under such regulatory circumstances, the ERJV participants might be faced with the risk of becoming a noncompliant (or administratively sanctioned) firm involuntarily because the rules are not enacted definitely. In addition, the lack of detailed rules might generate a disincentive to forming an ERJV. This

[30] For example, see Katsoulacos *et al.* (2001) and McDonald and Poyago-Theotoky (2012). Chiou and Hu (2001) examined environmental R&D formations under precommitment of an emission tax. McDonald and Poyago-Theotoky (2012) and Poyago-Theotoky (2007, footnote 2) presented important explanations about the misleading analysis conducted by Chiou and Hu (2001).

[31] The EU's antitrust guidelines for the horizontal cooperation agreements are "Guidelines on the applicability of Article 101 of the Treaty on the Functioning of the European Union to horizontal co-operation agreements." These appear on the European Commission's website (URL: http://ec.europa.eu/competition/antitrust/legislation/horizontal.html). Regarding the US guidelines for JV, the Federal Trade Commission (FTC) and the U.S. Department of Justice (DOJ) issued "Antitrust Guidelines for Collaborations Among Competitors" on the FTC's website (URL: http://www.ftc.gov/os/2000/04/ftcdojguidelines.pdf). Caloghirou *et al.* (2003), Caloghirou *et al.* (2004) and Motta (2004, Chapters 1 and 4) reported historical, legal, and economic explanations for RJV. Grossman and Shapiro (1986) provided important arguments related to RJV and antitrust guidelines. These studies are useful for understanding the antitrust policies of influential countries and regions.

[32] For details, see the website of JFTC (URL: http://www.jftc.go.jp/en/).

research provides theoretical findings to improve such weak points.

Some directions for future research are described below. First, the case of an asymmetric spillover parameter must be analyzed in line with Atallah's (2005a, 2005b, 2007) examinations. Second, it is necessary to explore the case of price competition in a differentiated duopoly. Third, it is important to examine environmental R&D cooperation in a vertical relation.

Appendix A

Proof of Proposition 1: Differentiation between π_{CJ} and π_{C} is given as

$$\pi_{\mathrm{CJ}} - \pi_{\mathrm{C}} = \frac{2\gamma(1-\beta)BA^2}{\Delta^2[\Delta^{\beta=1}]^2} \geq 0, \tag{3}$$

where $B \equiv [2d^2+3d-1]^2[8d(3+2d)+\gamma(1+d)^2][2d(2d+3)(1+\beta)^2+\gamma(1+d)^2] > 0$, $\Delta \equiv 2\gamma(1+d)^2+4d(3+2d)(1+\beta)^2 > 0$, and $\Delta^{\beta=1} \equiv 2\gamma(1+d)^2+16d(3+2d) > 0$. Only when $\beta = 1$, then $\pi_{\mathrm{CJ}} = \pi_{\mathrm{C}}$.

Poyago-Theotoky (2007) proves that $\pi_{\mathrm{C}} > \pi_{\mathrm{N}}$. In fact, from Equation (16) in Poyago-Theotoky (2007, p.70),

$$\pi_{\mathrm{C}} - \pi_{\mathrm{N}} = \frac{A^2(1+d)^2\kappa^2}{4\Delta^2\Gamma^2} > 0, \tag{4}$$

where $\kappa \equiv d(3-2d)(1-\beta)(1+\beta)^2+2\gamma[d+\beta(2d^2+2d-1)]$ and $\Gamma \equiv 2\gamma(1+d)^2+d(1+\beta)[3(3+\beta)+d(7+\beta)] > 0$.

Equations (3) and (4) show that each firm invariably has some private incentives for ERJV cartelization. Therefore, we have that $\pi_{\mathrm{CJ}} \geq \pi_{\mathrm{C}} > \pi_{\mathrm{N}}$ for all $d > \underline{d}$, $\gamma > 0$ and $\beta \in [0,1]$. $\square$

Appendix B

Proof of Proposition 2: After some manipulation, the difference between SW_{CJ} and SW_{C} is derived as

$$SW_{\mathrm{CJ}} - SW_{\mathrm{C}} = \frac{4(1-\beta)(3+\beta)LA^2}{[\Delta^{\beta=1}]^2\Delta^2} \geq 0,$$

where

$$\begin{aligned} L \equiv\ & 32d^3(3+2d)^2(5+2d)(1+\beta)^2+8d^2(3+2d)[4(1+d)(3+2d) \\ & +(1+\beta)^2(48d^5+216d^4+292d^3+76d^2-51d+5)]\gamma \\ & +2d(1+d)^2[64d^5+446d^3+155d^2-64d+3 \\ & +(1+\beta)^2(2d^2+3d-1)(8d^3+26d^2+21d+1)]\gamma^2 \\ & +(1+d)^4(2d^2+3d-1)(2d^2+5d+1)\gamma^3 > 0. \end{aligned}$$

$\Delta(>0)$ and $\Delta^{\beta=1}(>0)$ are both defined in Appendix A. Therefore, we have $SW_{\mathrm{CJ}} \geq SW_{\mathrm{C}}$ for all $d > \underline{d}$, $\gamma > 0$ and $\beta \in [0,1]$. $\square$

Appendix C

Welfare comparison: We obtain the following result.

$$SW_{\mathrm{CJ}} - SW_{\mathrm{N}} = \frac{J(d,\gamma;\beta)A^2}{[\Delta^{\beta=1}]^2\Gamma^2} \gtreqless 0$$

Therein,

$$\begin{aligned}
J(d,\gamma;\beta) &\equiv y + 8\gamma[k_0 + k_1\gamma + k_2\gamma^2], \\
y &\equiv -64d^3(1-\beta)(1+\beta)^2(1+d)^2(2d-3)[21+51d+26d^2 \\
&\quad +\beta(3+13d+6d^2)] \gtreqless 0, \\
\lambda_3 &\equiv 32d^5 + 201d^4 + 324d^3 + 154d^2 - 12d + 9 > 0, \\
\lambda_2 &\equiv 768d^5 + 2457d^4 + 2924d^3 + 994d^2 - 180d + 81 > 0, \\
\lambda_1 &\equiv 2720d^5 + 7735d^4 + 8172d^3 + 2278d^2 - 452d + 279 > 0, \\
\lambda_0 &\equiv 1216d^5 + 2023d^4 + 132d^3 - 1666d^2 - 156d + 687 > 0, \\
k_0 &\equiv d^2\{(1-\beta)[4(1+\beta)[16(3+\beta) + (1+\beta)(1-\beta)]d^6 + \lambda_3\beta^3 + \lambda_2\beta^2 \\
&\quad +\lambda_1\beta + \lambda_0] + 128(1+d)^2(2d+1)(2d+3)(2d^2+3d-1)\} > 0, \\
k_1 &\equiv 2d(1+d)^2\{(1-\beta)[d^2(d+1)(d+2)\beta^3 + d(1+d)(2d^3+14d^2 \\
&\quad +16d-1)\beta^2 + d(8d^4+101d^3+200d^2+91d-19)\beta + 94d^5 \\
&\quad +406d^4 + 499d^3 + 72d^2 - 112d + 5\beta + 27] \\
&\quad +4[20d^5 + 144d^4 + 170d^3 + 50d^2 - 2d - 9]\} > 0, \\
k_2 &\equiv (1+d)^4\{(1-\beta)[8d^2 + 4(5+\beta)d + 7 + 3\beta]d^2 \\
&\quad +4d^4 + 4d^3 + d^2 + 2(4+\beta)d - 3\} > 0.
\end{aligned}$$

In addition, $\Delta^{\beta=1}(>0)$ and $\Gamma(>0)$ are both defined in Appendix A. It is straightforward to verify the sign of each of the definitions presented above.

If $\underline{d} < d \leq 3/2$, then $y \geq 0$ for all $\beta \in [0,1)$. Therefore, when $\underline{d} < d \leq 3/2$, then $J(d,\gamma;\beta) \geq 0$; i.e., $SW_{\mathrm{CJ}} \geq SW_{\mathrm{N}}$ irrespective of the value of γ. However, when $d > 3/2$, then $y < 0$ for all $\beta \in [0,1)$. Therefore, when $d > 3/2$, then the sign of $J(d,\gamma;\beta)$ is indeterminate. As portrayed in Figure 1, $SW_{\mathrm{CJ}} \geq (<) SW_{\mathrm{N}}$ for all $\gamma \geq (<) \gamma_{JV} \equiv \{\gamma(>0) | J(d,\gamma;\beta) = 0, d > 3/2\}$. From the definition of $J(d,\gamma;\beta)$, verifying the existence and uniqueness of γ_{JV} is straightforward.

Furthermore, assuming that $d > 3/2$, only when $\beta = 1$, we have $y = 0$; i.e., $SW_{\mathrm{CJ}} > SW_{\mathrm{NJ}}$. This observation readily implies that there invariably exists some Region IV unless $\beta = 1$.

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