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Environmental research joint ventures in a Cournot duopoly under emission taxes and environmental corporate social responsibility with managerial delegation

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Abstract

This paper examines both the rule of when environmental research joint venture (ERJV) is socially allowable and the optimal emission taxation, assuming a situation in which the government imposes a pollution emission tax on polluting Cournot duopolists whose owners delegate managerial decision-making rights to managers who adopt environmental CSR (ECSR) behavior. The findings of this paper are threefold. First, strategic manipulation of the emissions tax rate, which incentivizes each manager to choose ERJV cooperation, is preferable from the perspective of social welfare. This strategic manipulation contributes to softening the decline in social welfare. Second, government antitrust authorities should always permit the ERJV. This policy recommendation is valid even if decision-making on ERJVs by government antitrust authorities is conducted at the same time as or after decision-making on the emissions tax rate. Third, this paper provides an economic foundation in support of legislating the disclosure of managerial remuneration contracts in ECSR firms.

Keywords: Environmental research joint ventures; Corporate social responsibility; Emission tax; Cournot duopoly; Managerial delegation.
JEL Classification: L24; M14; O38; Q58

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1. Introduction

As environmental issues have become more serious worldwide in recent decades, environmental corporate social responsibility (ECSR) has received greater attention. Accordingly, the vast majority of firms increasingly emphasize the disclosure of ECSR behavior and publish ECSR/sustainability reports. According to KPMG (2020, p. 10), the rate of public disclosure of sustainability reports began to increase rapidly after the beginning of the 21st century. Since firms cannot ignore consumers' reputations and the preferences of their owners (shareholders), including environmental activists, many firms have adapted their ECSR behaviors.[1] In other words, adaptation to ECSR is one of the strategies for survival in the market. In addition, many studies on ECSR have been conducted in the fields of business administration and economics.

One of the traditional features of economics is that analysis is based on the assumption that private firms are profit maximizers. This assumption is employed by seminal studies by Gersbach and Requate (2004), Poyago-Theotoky (2007), Montero (2002), Puller (2006), and Requate and Unold (2003) on environmental innovation and environmental regulation in oligopolistic markets.[2] These studies have reported important findings and insightful policy implications. In reality, however, considerably more firms are adopting ECSR. In addition, it is practically difficult for governments to restrict firms from voluntarily adapting to CSR. Even if the category of CSR is limited to strategic CSR, a large gap exists between the assumption of profit-maximizing firms and the reality of an increasing number of firms strategically adapting to ECSR.[3] This fact strongly suggests that economic research should focus on ECSR firms that strategically maximize objective functions other than profit to obtain higher profits.

In recent years, the delegation models of Fershtman and Judd (1987), Sklivas (1987), and Vickers (1985) have been applied in theoretical studies of strategic ECSR with environmental R&D investment (Buccella et al. (2022, 2023), Poyago-Theotoky and Yong (2019), Xing and Lee (2023)).[4] However, the number of these studies is inadequate. Previous studies have focused on how a remuneration contract between the owners of a firm and the manager affects economic welfare. However, when we turn our perspective to the ERJV, fundamental questions related to competition policy remain. First, when does a manager with delegated management rights have a private incentive to form an ERJV? Second, when should ERJV by ECSR firms be socially allowable? To our knowledge, no answers have been given to any of these research questions. This indicates that only inadequate basic theoretical research has been conducted to design competition policy and environmental regulation.

To answer these questions on environmental research joint ventures (ERJVs) from a theoretical perspective, this paper extends the Cournot duopoly model with ECSR under emission taxes constructed by Xing and Lee (2023). The extended model of this paper results in two theoretical contributions. The first

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[1] Tomoda and Ouchida (2023) explains a mechanism by which ECSR and non-ECSR firms rise through stock market adjustments by explicitly incorporating the presence of environmental activists as shareholders in the model.
[2] For other environmental R&D studies, see Buccella et al. (2021), Cabon-Dhersin and Raffin (2024), Chen et al. (2022), Hattori (2017), Lambertini et al. (2017), Ouchida and Goto (2016a, 2016b, 2022), and others.
[3] Crifo and Forget (2015), Kitzmueller and Shimshack (2012), Lyon and Maxwell (2008), and Schmitz and Schrader (2015) present excellent surveys on CSR and explain strategic CSR. For the categorization of CSR, see Kitzmueller and Shimshack (2012, Figure 2).
[4] For other ECSR studies, see Iannucci and Tampieri (2023), Fukuda and Ouchida (2020), Hirose et al. (2020), Hirose and Matsumura (2022), Lambertini and Tampieri (2015, 2023), Nie et al. (2019), Pal (2012), Villena and Quinteros (2024), and Wang (2021).

improves the modeling of spillover effects from environmental R&D investments. Many studies that analyze environmental R&D investment, such as Poyago-Theotoky (2007) and Chiou and Hu (2001), have applied the formulation of the spillover effect by d'Aspremont and Jacquemin (1988).[5] Unlike those previous studies, this paper applies the formulation of Macho-Stadler et al. (2021) to avoid the unnatural situation in which even noninvesting firms can enjoy the technological spillover effects from rival firms. Another contribution is the development of an extended ECSR model that explicitly incorporates the ERJV into a pure Cournot duopoly model with ECSR. The new formulation of ERJV in this paper enables us to deepen the debate on whether ERJV formation by ECSR firms is socially preferable.

The findings of this paper are threefold. First, strategic manipulation of the emissions tax rate, which incentivizes each manager to choose ERJV cooperation, is preferable from the perspective of social welfare. Consequently, this strategic manipulation contributes to softening the decline of social welfare. The second contribution is to competition policy. We present the policy recommendation that government antitrust authorities should invariably permit ERJV. This policy recommendation is valid even if the decision-making on ERJVs by government antitrust authorities is made at the same time as or after decision-making on the emissions tax rate. Third, this paper suggests that information on managers' remuneration contracts is necessary to make policy decisions on ERJV between ESCR firms. In other words, this paper provides an economic foundation for enacting legislation for the disclosure (or observability) of managers' remuneration contracts in ECSR firms.

The remainder of this paper is organized as follows. The second section introduces the managerial delegation model with ECSR under an emission tax policy. The third section provides some preliminary results. The fourth section examines the private and social superiorities among eight scenarios of environmental R&D organization, including ERJVs and technological spillover effects. The fifth section analyzes the conflicts of interest and choices between owners and managers. The sixth section examines optimal emissions taxation and clarifies the contributions of this paper and policy recommendations. The final section presents the conclusions. The appendix contains equilibrium outcomes, a brief sketch of the solution procedures, proofs, and calculation results.

2. Model

To analyze the competition policy for environmental R&D conducted by ECSR firms, this paper considers an environmental managerial delegation model under a precommitted emission tax.

2.1 Market

The work in this paper considers an industry that consists of two homogeneous firms (*i.e.*, firm i and firm j) engaged in Cournot competition with the same cost structure and emission-abatement technology. The utility of a representative consumer is

$$U(q_i, q_j, m) = a(q_i + q_j) - (1/2)(q_i + q_j)^2 + m. \tag{1}$$

[5] For other environmental R&D studies that apply the model by d'Aspremont and Jacquemin (1988), see Chiou and Hu (2001), Ouchida and Goto (2016a, 2016b, 2022), Bárcena-Ruiz et al. (2023), Haruna and Goel (2019), Lambertini and Tampieri (2023), Lambertini et al. (2017), Xing (2017), and Yong et al. (2018).

Here, the values of q_i and q_j denote firm i's and firm j's outputs, respectively; m signifies the consumption of a numeraire good; and $a(> 0)$ is the parameter of market size. Utility maximization yields the following inverse demand function:

$$p(q_i, q_j) = a - (q_i + q_j), i, j \in \{1,2\}, i \neq j. \tag{2}$$

The production of each good generates pollution. The value of each firm's emissions per unit of output is assumed to be one.[6] Suppose that two firms are faced with an emission tax rate t, which is determined by the government's environmental authorities. Each firm uses *end-of-pipe* technology for pollution abatement.[7] Firm i's emission abatement effort is denoted by z_i. When firm i's production level is q_i, emission reduction costs $(\gamma/2)z_i^2 - \delta z_i z_j, (\gamma > 2, \delta \in [0,1])$ enable firm i to abate emissions from a level of q_i to $e_i(q_i, z_i) \equiv q_i - z_i$. For firm i's emission reduction costs, parameter $\delta \in [0,1]$ represents the technological spillover effect from firm j to firm i. This setting applies the spillover effect formulated by Macho-Stadler et al. (2021). Firm i receives the cost-reducing effect for its own environmental R&D from the rival firm's pollution-abatement effort. A positive externality to lower emission reduction costs occurs only when two firms invest in environmental R&D. This setting differs significantly from the related literature (e.g., Ouchida and Goto (2016a, 2016b, 2022), Poyago-Theotoky (2007), Strandholm et al. (2018)), which somewhat unnaturally assumes that a firm can enjoy positive externalities from a rival firm's R&D investment even when it does not invest in R&D. Moreover, a lower (higher) value of $\gamma(> 2)$ denotes higher (lower) efficiency of the emission reduction cost.[8] Firm i's total cost $C_i(q_i, z_i)$ is additively separable with respect to production costs $cq_i, (c > 0)$ and emission reduction costs: $C_i(q_i, z_i) = cq_i + (\gamma/2)z_i^2 - \delta z_i z_j$.

When two firms form an ERJV, they voluntarily and fully share their technological information on environmental R&D. A feature of ERJVs is perfect spillover (*i.e.*, $\delta = 1$). This paper assumes that no fixed costs for ERJVs are necessary.

Thus, firm i's profit function is given by

$$\pi_i = \{a - (q_i + q_j)\}q_i - cq_i - t\{q_i - z_i\} - \{(\gamma/2)z_i^2 - \delta z_i z_j\}. \tag{3}$$

2.2 Environmental damage and the government

Firm i's net emissions $e_i(q_i, z_i)$ depend on both the output and the emission abatement effort. Total emissions $E \equiv \sum_{i=1}^{2} e_i(q_i, z_i)$ cause environmental damage $D(E) \equiv dE$, and $d(> 0)$ denotes the damage

[6] In general, when the emissions per unit output is $e_0(> 0)$, a firm's emissions are expressed by $e_0 q$. In line with the settings by Fukuda and Ouchida (2020), Poyago-Theotoky (2007), Strandholm et al. (2018, 2023), Xu et al. (2016) and others, this paper assumes $e_0 = 1$ to simplify the analysis.

[7] Activated carbon adsorption equipment and flue gas desulfurization equipment are examples of *end-of-pipe* technology (Ouchida and Goto (2016b, p.185)). *End-of-pipe* technology aims to abate emissions by eliminating them at the end of the production process, although it is not sufficient to reduce the emissions per unit output. As explained by Ouchida and Goto (2016b, footnote 13), environmental R&D investments in the quality improvement of the hydrodenitrogenation catalyst and desulfurization catalyst are applicable as examples of R&D efforts in *end-of-pipe* technology.

[8] The assumption of $\gamma > 2$ describes the reality that environmental R&D costs are not inexpensive. Furthermore, that assumption ensure that the sign of environmental R&D effort is positive.

coefficient.[9] Government environmental authorities impose an emissions tax rate $t(\geq 0)$ on the emission level to mitigate environmental damage. In this paper, the emission tax rate t is assumed to be given.[10]

Social welfare SW is defined as the sum of consumer surplus $CS \equiv (q_i+q_j)^2/2$, producers' profits $\pi_i + \pi_j$, and total tax revenues $T \equiv tE$ minus environmental damage $D(E)$: $SW \equiv CS + \pi_i + \pi_j + T - D(E)$.

2.3 Strategic environmental CSR

To develop an ECSR model, we assume that the owners of each firm employ a manager. We also assume no cross-ownership. Each manager determines environmental R&D formation, environmental R&D efforts, and the output level on behalf of the owners. In a managerial delegation model, the firm consists of owners who control the firm and each manager whose decision-making is based on an incentive contract that the owner designs. Similar to relevant studies (e.g., Fershtman and Judd (1987), Buccella et al. (2022), Poyago-Theotoky and Yong (2019)), the owners of firm $i(=1,2)$ offer a publicly observed contract to each manager. Manager $i(=1,2)$ receives remuneration R_i:

$$R_i \equiv G_i + H_i V_i \geq 0,\ G_i \geq 0, H_i \geq 0, \tag{4}$$

where $V_i > 0$ describes the incentive scheme for manager $i(=1,2)$. Without loss of generality, we assume $G_i = 0$ and $H_i = 1$ hereafter.

In this work, we assume that the owners of each firm take care of not only its own profit but also environmental damage. Thus, the objective function of manager i is described by

$$V_i \equiv \pi_i - \theta_i D(E), \tag{5}$$

where $\theta_i(\geq 0)$ represents firm i's degree of ECSR. A higher value of θ_i denotes a greater degree of ECSR. When $\theta_i = 0$, then firm i maximizes only its own profit. Conversely, when $\theta_i > 0$, then firm i behaves as an ESCR firm. The owners of firm i determine the level of θ_i required to maximize their own profit π_i. This paper assumes that the government cannot control the level of ECSR. The value of θ_i is publicly observed through the disclosure (or observability) of managers' remuneration contracts.

2.4 The timing of the game

This paper assumes that government environmental authorities have a precommitment ability to the emission tax rate. Under the given emissions tax rate t, this paper solves the following three-stage game. In stage 1, the owners of firm i choose the level of θ_i to maximize their own profit π_i or joint profits $(\pi_i + \pi_j)$. In stage 2, manager i chooses one of the following four R&D formations: noncooperative environmental R&D, cooperative environmental R&D, ERJV competition, or ERJV cooperation. Moreover, manager i determines the level of emission abatement effort z_i to maximize V_i or $V_i + V_j$. In stage 3, manager i determines the output level q_i to maximize V_i.

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[9] As noted by Xing and Lee (2023, footnote 9), it is impossible to derive the explicit equilibrium outcome if the damage function is quadratic. Thus, we employ a linear damage function. However, the linear damage function is plausible. From the perspective of environmental epidemiology, the dose–response function can be interpreted as linear. This paper describes a situation in which the toxicity of pollutions emitted by firms is not excessively strong.

[10] In Section 6, we relax this assumption and examine the optimal emissions taxation.

2.5 Eight scenarios

The owners of each firm choose the ECSR level, whereas the manager of each firm determines the emission abatement and output levels. To analyze competition policy for the environmental R&D conducted by ECSR firms, we consider the following eight scenarios (see Table 1): noncooperative ECSR and noncooperative environmental R&D [Scenario I]; noncooperative ECSR and cooperative environmental R&D [Scenario II]; noncooperative ECSR and ERJV competition [Scenario III]; noncooperative ECSR and ERJV cooperation [Scenario IV]; cooperative ECSR and noncooperative environmental R&D [Scenario V]; cooperative ECSR and cooperative environmental R&D [Scenario VI]; cooperative ECSR and ERJV competition [Scenario VII]; and cooperative ECSR and ERJV cooperation [Scenario VIII]. We assume that government antitrust authorities prohibit collusive behavior in the production stage.

Table 1: Eight scenarios

	ECSR	Environmental R&D	Production
Scenario I	Competition	Competition	Competition
Scenario II	Competition	Cooperation	Competition
Scenario III	Competition	ERJV competition	Competition
Scenario IV	Competition	ERJV cooperation	Competition
Scenario V	Cooperation	Competition	Competition
Scenario VI	Cooperation	Cooperation	Competition
Scenario VII	Cooperation	ERJV competition	Competition
Scenario VIII	Cooperation	ERJV cooperation	Competition

3 Equilibrium outcomes

This section analyzes eight scenarios using backward induction and provides a brief sketch of the solution procedures. A solution concept is the subgame-perfect Nash equilibrium (SPNE). The procedures for deriving solutions for scenarios IV, VII, and VIII are explained here for a clearer understanding of the subsequent sections, whereas explanations for other scenarios are provided in Appendix A. The equilibrium outcomes are summarized in Tables A1(I)-(VIII) in Appendix B.

3.1 Scenario IV: Noncooperative ECSR and ERJV cooperation

In this case, both firms form an ERJV and voluntarily and fully share their technological information on pollution abatement, which is characterized by $\delta = 1$.

In stage 3, manager i noncooperatively determines q_i to maximize the objective function:

$$\begin{aligned} V_i(q_i, q_j) &= \pi_i - \theta_i D(E) \\ &= \{A - (q_i + q_j)\}q_i - t\{q_i - z_i\} - \{(\gamma/2)z_i^2 - \delta z_i z_j\} \\ &\quad -\theta_i d\{q_i - z_i + q_j - z_j\}. \end{aligned} \tag{6}$$

Therein, $A \equiv a - c > 0$. From the corresponding first-order conditions for maximization $\partial V_i/\partial q_i = 0 = \partial V_j/\partial q_j$, the equilibrium output levels of the two firms are

$$q_i(\theta_i, \theta_j) = \frac{A - t - d(2\theta_i - \theta_j)}{3}, \tag{7}$$

$$q_j(\theta_i,\theta_j) = \frac{A - t - d(2\theta_j - \theta_i)}{3}. \tag{8}$$

Throughout this paper, we assume that $A > 5t$ to ensure a positive value of the equilibrium output level and equilibrium pollution emission (see Part (ii) of Assumption 1 in Section 4). This assumption implies that demand is large enough. The equilibrium outputs in (7) and (8) depend not on the environmental R&D effort level but on the ECSR level. Thus, equilibrium output in stage 3 is equivalent to the case in which decisions in stages 2 and 3 are made at the same time.

In stage 2, manager i cooperatively determines z_i to maximize the summation of two objective functions:

$$\begin{aligned} V_i(z_i,z_j) + V_j(z_i,z_j) = {}& \{A - (q_i(\theta_i,\theta_j) + q_j(\theta_i,\theta_j))\}q_i(\theta_i,\theta_j) - t\{q_i(\theta_i,\theta_j) - z_i\} \\ & -\{(\gamma/2)z_i^2 - z_i z_j\} - \theta_i d\{q_i(\theta_i,\theta_j) - z_i + q_j(\theta_i,\theta_j) - z_j\} \\ & +\{A - (q_i(\theta_i,\theta_j) + q_j(\theta_i,\theta_j))\}q_j(\theta_i,\theta_j) - t\{q_j(\theta_i,\theta_j) - z_j\} \\ & -\{(\gamma/2)z_j^2 - z_i z_j\} - \theta_j d\{q_i(\theta_i,\theta_j) - z_i + q_j(\theta_i,\theta_j) - z_j\}. \end{aligned} \tag{9}$$

From the corresponding first-order conditions for maximization $\partial(V_i(z_i,z_j) + V_j(z_i,z_j))/\partial z_i = 0 = \partial\,(V_i(z_i,z_j) + V_j(z_i,z_j))/\partial z_j$, the equilibrium R&D effort levels are obtained as

$$z_i(\theta_i,\theta_j) = \frac{d(\theta_i + \theta_j) + t}{\gamma - 2}, \tag{10}$$

$$z_j(\theta_i,\theta_j) = \frac{d(\theta_i + \theta_j) + t}{\gamma - 2}. \tag{11}$$

In stage 1, the owners of firm i noncooperatively choose θ_i to maximize its own profit: $\pi_i(\theta_i,\theta_j) = \{A - (q_i(\theta_i,\theta_j) + q_j(\theta_i,\theta_j))\}q_i(\theta_i,\theta_j) - t\{q_i(\theta_i,\theta_j) - z_i(\theta_i,\theta_j)\} - \{[z_i(\theta_i,\theta_j)]^2 - z_i(\theta_i,\theta_j)z_j(\theta_i,\theta_j)\}$. The first-order condition for maximization is derived as $\partial\pi_i/\partial\theta_i < 0$. Thus, the equilibrium ECSR levels are obtained as

$$\theta_i^{\mathrm{IV}} = 0,\ \theta_j^{\mathrm{IV}} = 0. \tag{12}$$

Equation (12) shows that owners do not adopt ECSR under scenario IV. By using (12), other equilibrium values of the full game are obtained, as shown in Table A1(IV).

3.2 Scenario VII: Cooperative ECSR and ERJV competition

As in Subsection 3.1 (the case of scenario IV), two firms form an ERJV. Then, both firms fully share technological information on pollution abatement ($\delta = 1$).

In stage 3, manager i noncooperatively determines the output level q_i to maximize $V_i(z_i,z_j)$. The equilibrium output level is identical to that in Subsection 3.1. In stage 2, manager i noncooperatively determines z_i to maximize $V_i(z_i,z_j)$:

$$\begin{aligned} V_i(z_i,z_j) = {}& \{A - (q_i(\theta_i,\theta_j) + q_j(\theta_i,\theta_j))\}q_i(\theta_i,\theta_j) - t\{q_i(\theta_i,\theta_j) - z_i\} \\ & -\{(\gamma/2)z_i^2 - z_i z_j\} - \theta_i d\{q_i(\theta_i,\theta_j) - z_i + q_j(\theta_i,\theta_j) - z_j\} \end{aligned} \tag{13}$$

From the corresponding first-order conditions for maximization $\partial V_i(z_i,z_j)/\partial z_i = 0 = \partial V_j(z_i,z_j)/\partial z_j$, equilibrium R&D effort levels are derived as

$$z_i(\theta_i,\theta_j) = \frac{d(\gamma\theta_i + \theta_j) + (\gamma + 1)t}{(\gamma + 1)(\gamma - 1)}, \tag{14}$$

$$z_j(\theta_i,\theta_j)=\frac{d(\theta_i+\gamma\theta_j)+(\gamma+1)t}{(\gamma+1)(\gamma-1)}. \tag{15}$$

In stage 1, the owners of firm i cooperatively determine θ_i to maximize the joint profits:

$$\begin{aligned}\pi_i(\theta_i,\theta_j)+\ \pi_j(\theta_i,\theta_j)&\\ =\ &\{A-(q_i(\theta_i,\theta_j)+q_j(\theta_i,\theta_j))\}q_i(\theta_i,\theta_j)-t\{q_i(\theta_i,\theta_j)-z_i(\theta_i,\theta_j)\}\\ &-\{(\gamma/2)[z_i(\theta_i,\theta_j)]^2-z_i(\theta_i,\theta_j)z_j(\theta_i,\theta_j)\}\\ &+\{A-(q_i(\theta_i,\theta_j)+q_j(\theta_i,\theta_j))\}q_j(\theta_i,\theta_j)-t\{q_j(\theta_i,\theta_j)-z_j(\theta_i,\theta_j)\}\\ &-\{(\gamma/2)[z_j(\theta_i,\theta_j)]^2-z_i(\theta_i,\theta_j)z_j(\theta_i,\theta_j)\}.\end{aligned} \tag{16}$$

The first-order conditions for maximization are $\partial(\pi_i(\theta_i,\theta_j)+\pi_j(\theta_i,\theta_j))\ /\partial\theta_i=0=\partial(\pi_i(\theta_i,\theta_j)+\pi_j(\theta_i,\theta_j))/\partial\theta_j$. Thus, the equilibrium ECSR levels are obtained as

$$\theta_i^{\mathrm{VII}}=\frac{A(\gamma-1)^2-(\gamma-4)(\gamma+2)t}{d(4+(\gamma-2)(4\gamma+9))}, \tag{17}$$

$$\theta_j^{\mathrm{VII}}=\frac{A(\gamma-1)^2-(\gamma-4)(\gamma+2)t}{d(4+(\gamma-2)(4\gamma+9))}. \tag{18}$$

Table A1(VII) summarizes all equilibrium values of scenario VII.[11]

3.3 Scenario VIII: Cooperative ECSR and ERJV cooperation

In this case, two firms form an ERJV, and they perfectly share information on pollution abatement technology (*i.e.*, $\delta=1$). In stage 3, manager i noncooperatively chooses q_i to maximize $V_i(z_i,z_j)$. The equilibrium output level is identical to that in Subsection 3.1.

In stage 2, manager i cooperatively determines the abatement level z_i to maximize $V_i(z_i,z_j)+V_j(z_i,z_j)$:

$$\begin{aligned}V_i(z_i,z_j)+V_j(z_i,z_j)=&\{A-(q_i(\theta_i,\theta_j)+q_j(\theta_i,\theta_j))\}q_i(\theta_i,\theta_j)-t\{q_i(\theta_i,\theta_j)-z_i\}\\ &-\{(\gamma/2)z_i^2-z_iz_j\}-\theta_i d\{q_i(\theta_i,\theta_j)-z_i+q_j(\theta_i,\theta_j)-z_j\}\\ &+\{A-(q_i(\theta_i,\theta_j)+q_j(\theta_i,\theta_j))\}q_j(\theta_i,\theta_j)-t\{q_j(\theta_i,\theta_j)-z_j\}\\ &-\{(\gamma/2)z_j^2-z_iz_j\}-\theta_j d\{q_i(\theta_i,\theta_j)-z_i+q_j(\theta_i,\theta_j)-z_j\}.\end{aligned} \tag{19}$$

From the corresponding first-order conditions for maximization $\partial(V_i(z_i,z_j)+V_j(z_i,z_j))/\partial z_i=0=\partial(V_j(z_i,z_j)+V_j(z_i,z_j))/\partial z_j$, equilibrium R&D effort levels are derived as

$$z_i(\theta_i,\theta_j)=\frac{d(\theta_i+\theta_j)+t}{\gamma-2}, \tag{20}$$

$$z_j(\theta_i,\theta_j)=\frac{d(\theta_i+\theta_j)+t}{\gamma-2}. \tag{21}$$

In stage 1, the owners of firm i cooperatively determine the value of θ_i to maximize the joint profits:

$$\begin{aligned}\pi_i(\theta_i,\theta_j)+\ \pi_j(\theta_i,\theta_j)&\\ =\ &\{A-(q_i(\theta_i,\theta_j)+q_j(\theta_i,\theta_j))\}q_i(\theta_i,\theta_j)-t\{q_i(\theta_i,\theta_j)-z_i(\theta_i,\theta_j)\}\\ &-\{(\gamma/2)[z_i(\theta_i,\theta_j)]^2-z_i(\theta_i,\theta_j)z_j(\theta_i,\theta_j)\}\\ &+\{A-(q_i(\theta_i,\theta_j)+q_j(\theta_i,\theta_j))\}q_j(\theta_i,\theta_j)-t\{q_j(\theta_i,\theta_j)-z_j(\theta_i,\theta_j)\}\\ &-\{(\gamma/2)[z_j(\theta_i,\theta_j)]^2-z_i(\theta_i,\theta_j)z_{nj}(\theta_i,\theta_j)\}.\end{aligned} \tag{22}$$

[11] Under the assumption of $A>5t$, it is straightforward to verify that $\theta_i^{\mathrm{VII}}>0$.

The first-order conditions for maximization are $\partial(\pi_i(\theta_i,\theta_j)+\pi_j(\theta_i,\theta_j))\,/\partial\theta_i = 0 = \partial(\pi_i(\theta_i,\theta_j)+\pi_j(\theta_i,\theta_j))/\partial\theta_j$. Thus, the equilibrium ECSR levels are derived as

$$\theta_i^{\mathrm{VIII}} = \frac{(A-t)(\gamma-2)}{4d(\gamma+7)}, \tag{23}$$

$$\theta_j^{\mathrm{VIII}} = \frac{(A-t)(\gamma-2)}{4d(\gamma+7)}. \tag{24}$$

Other equilibrium values of scenario VIII are listed in Table A1(VIII).

4. Comparison

In this section, we compare the equilibrium outcomes of eight scenarios. From Table A1(I-VIII), we straightforwardly obtain the following propositions (see Appendices C-K for the proofs and supporting information).

Proposition 1. *Given the same emission tax rate, the ranking of the level of ECSR is* $\theta^{\mathrm{VII}} \geq \theta^{\mathrm{V}} > \theta^{\mathrm{VI}} \geq \theta^{\mathrm{VIII}} > \theta^{\mathrm{I}} = \theta^{\mathrm{II}} = \theta^{\mathrm{III}} = \theta^{\mathrm{IV}} = 0$.

Proposition 1 shows that no firm adopts ECSR under noncooperative ECSR scenarios. Firms only adopt ECSR if both firms cooperate in the ECSR stage. Proposition 1 is explained as follows. The difference in firms' behavior between scenario V and scenario VI is the presence or absence of coordination in environmental R&D investment. After the owners of each firm have determined the degree of cooperative ECSR, if environmental R&D cooperation is chosen, the free-riding effect is reduced because the technological spillover effect is internalized through R&D investment coordination. This leads to a greater level of R&D investment in the case of environmental R&D cooperation than in the case of noncooperative R&D, resulting in excessive R&D investment.[12] Therefore, when R&D cooperation is chosen at stage 2, the owners of ESCR firms prefer a smaller ECSR to discourage aggressive environmental R&D investment when determining the level of ESCR at stage 1.[13] Turning to the spillover effect (δ), as the degree of δ increases, the cost of pollution abatement decreases. Furthermore, environmental R&D competition in scenario V results in fierce R&D investment because the spillover effect is not internalized. Therefore, ECSR levels increase to encourage greater environmental R&D investment.[14] In scenario VI, R&D investment increases because pollution abatement costs decline gradually as spillover effects increase, but the level of ECSR decreases to discourage environmental R&D investment.[15] Thus, we obtain $\theta^{\mathrm{VII}} \geq \theta^{\mathrm{V}}$ and $\theta^{\mathrm{VI}} \geq \theta^{\mathrm{VIII}}$.

We clarify the difference between Proposition 1 of Xing and Lee (2023) and Proposition 1 in the present paper. Xing and Lee (2023) assume that there is no technological spillover effect and show that $\theta^{\mathrm{V}} > \theta^{\mathrm{VI}} > \theta^{\mathrm{I}} = \theta^{\mathrm{II}} = 0$. In contrast, we incorporate the technological spillover effect and ERJV scenarios into their analytical framework and show that ECSR cooperation under ERJV competition (scenario VII) yields the highest level of ECSR.

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12 Given the same value of ECSR, θ, we have $z^{\mathrm{VI}} - z^{\mathrm{V}} = \frac{d\theta[\gamma+(\gamma-2\delta)(\gamma-1)]+\delta t}{(\gamma-2\delta)(\gamma-\delta)} > 0$.

13 See Xing and Lee (2023, Section 4.1).

14 $\frac{\partial\theta^{\mathrm{V}}}{\partial\delta} = \frac{9[2A(\gamma-\delta)\delta+(4\gamma^2+(9-2\delta)\gamma-2\delta^2)]}{d[4\gamma^2+\gamma(9-8\delta)+2\delta(2\delta-9)]^2} > 0$.

15 $\frac{\partial\theta^{\mathrm{VI}}}{\partial\delta} = -\frac{9(A-t)}{2d(9+\gamma-2\delta)^2} < 0$.

In the subsequent comparisons, the results depend on several parameters. Hereinafter, for simplicity, we make the following assumption:

Assumption 1. (i) $\gamma = 3$, (ii) $A > 5t$.

Part (i) of Assumption 1 does not essentially affect the validity of the subsequent analysis. Part (ii) of Assumption 1 ensures a positive value of the equilibrium output level and equilibrium pollution emission in all scenarios when $\gamma = 3$. Part (ii) of Assumption 1 implies that demand is large enough.

Under Assumption 1, we have the following proposition.[16]

Proposition 2. *When the emissions tax rate is low* $(0 < t < (3/35)A)$*, the environmental R&D effort level under cooperative ECSR and ERJV competition (i.e., scenario VII) is greater than that under the other seven scenarios. When the emissions tax rate is high* $((3/35)A < t < (1/5)A)$*, the environmental R&D effort level under cooperative ECSR and ERJV cooperation (i.e., scenario VIII) is greater than that under the other seven scenarios.*

Proposition 2 states that an ERJV under cooperative ECSR yields greater pollution abatement (environmental R&D levels) than any other scenario does. Xing and Lee (2023, Proposition 2) show that $z^{\mathrm{V}} > z^{\mathrm{VI}} > z^{\mathrm{II}} = z^{\mathrm{I}}$. In contrast, this proposition refines the results of Xing and Lee (2023, Proposition 2) by incorporating the ERJV and the technological spillover effect. The intuitive explanation behind Proposition 2 is as follows. When the emissions tax rate is low, the incentive for firms to invest in environmental R&D is relatively small. In scenario VII (ERJV competition under cooperative ECSR), however, the degree of ECSR and the technological spillover effect increase, whereas environmental R&D competition intensifies. As a result, scenario VII results in greater emission reduction. Conversely, when the emissions tax rate is high, the incentive for firms to invest in emission abatement becomes relatively large. Additionally, the level of environmental R&D investment increases as the technological spillover effect increases, but when the tax rate is high, the managers of both firms increase their R&D investment (pollution abatement) under ERJV cooperation.

With respect to the output, the following proposition is obtained.

Proposition 3. *Under Assumption 1,* $q^{\mathrm{I}} = q^{\mathrm{II}} = q^{\mathrm{III}} = q^{\mathrm{IV}} > q^{\mathrm{VIII}} \geq q^{\mathrm{VI}} > q^{\mathrm{V}} \geq q^{\mathrm{VII}}$ *holds.*

Proof of Proposition 3 is given in Appendix F. Proposition 3 shows that the output level (consumer surplus) is greater when the owners of a firm do not adopt ECSR behavior than in the case of ECSR. When the owners of each firm adopt cooperative ECSR, environmental R&D competition results in lower outputs than environmental R&D cooperation. The reason for this result is that the level of ECSR determined by owners increases when R&D investment is noncooperative (Xing and Lee (2023, p.2689)). In fact, the output ranking derived in Proposition 3 is the opposite of the ranking of ECSR levels obtained in Proposition 1.[17]

The following proposition is derived for the amount of pollution.

[16] The proof is given in Appendix D. The ranking of environmental R&D effort levels is derived in Appendix E.

[17] Xing and Lee (2023, Proposition 3) show that $q^{\mathrm{I}} = q^{\mathrm{II}} > q^{\mathrm{VI}} > q^{\mathrm{V}}$.

Proposition 4. *Under Assumption 1, pollution emissions under cooperative ECSR and ERJV competition (i.e., scenario VII) are lower than those under any of the other seven scenarios if* $\delta \in [0,1)$. *However, pollution emissions under noncooperative ECSR and noncooperative environmental R&D (i.e., scenario I) are greater than those under any of the other seven scenarios if* $\delta \in (0,1)$.

The proof of Proposition 4 is given in Appendix G. The intuitive explanation behind Proposition 4 is as follows. First, from Proposition 2, when the emissions tax rate is relatively low, the environmental R&D effort (emission abatement) under scenario VII is the largest among the eight scenarios. Furthermore, when the emission tax rate is relatively high, the environmental R&D effort (emission abatement) under scenario VIII is the largest among the eight scenarios, but the emission abatement under scenario VII is also relatively large. From Proposition 3, the output in scenario VII is always the smallest among the eight scenarios. Therefore, when the tax rate is low, the amount of pollution emissions in scenario VII is the smallest among the eight scenarios. Moreover, even when the tax rate is relatively high, the amount of pollution emissions in scenario VII is the smallest among the eight scenarios because the output level is sufficiently small. The background of the scenario with the largest amount of pollution is explained as follows. According to Appendix E, scenario I yields the smallest environmental R&D effort. Additionally, Proposition 3 shows that scenarios I and II generate the largest outputs. Therefore, the amount of pollution emissions in scenario I becomes the largest among the eight scenarios.

Regarding the net profit, we obtain the following proposition.

Proposition 5. *Under Assumption 1, each firm's net profit under cooperative ECSR and ERJV competition (i.e., scenario VII) is greater than that under any of the other seven scenarios.*

Proof of Proposition 5 is provided in Appendix H. Proposition 5 implies that the owners of each firm always prefer scenario VII.[18] Thus, the owners of each firm invariably choose cooperative ECSR. As shown in Proposition 3, the output level becomes greater when a noncooperative ECSR is chosen; conversely, the output level decreases when a cooperative ECSR is chosen. Xing and Lee (2023, p.2689) explain that the key factor in profit comparison is the decline in output resulting from a higher ECSR and that the decline in output is an inexpensive way to reduce pollution. This explanation is also valid for this paper. However, because ERJV and spillover effects are newly incorporated in this paper, their features should be reflected in our explanation. The formation of an ERJV achieves perfect spillover, which generates a large decrease in pollution abatement costs. In contrast, in scenario VII, perfect spillover through the ERJV causes fierce environmental R&D competition, resulting in greater pollution abatement costs. At the same time, another effect exists. A perfect spillover will significantly increase the ECSR and further increase the environmental R&D level. These effects result not only in lower production and lower profits but also in significantly lower tax payments. The large decrease in tax payments in scenario VII contributes to the largest profit among the eight scenarios. Therefore, the owners of the firm prefer scenario VII.

Regarding the remuneration of managers, we obtain the following proposition.

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[18] Xing and Lee (2023, Proposition 4) compare scenarios I-IV and show that $\pi^{\mathrm{III}} > \pi^{\mathrm{IV}} > \pi^{\mathrm{II}} = \pi^{\mathrm{I}}$.

Proposition 6. *When* $t < \left(-59 + 3\sqrt{745}\right)A/130$*, the remuneration of managers under noncooperative ECSR and ERJV cooperation (i.e., scenario IV) is greater than that under any of the other seven scenarios. On the other hand, when* $t > \left(-59 + 3\sqrt{745}\right)A/130$*, the remuneration of managers under cooperative ECSR and ERJV competition (i.e., scenario VII) is greater than that under any of the other seven scenarios.*

The proof of Proposition 6 is given in Appendix I. Proposition 6 implies that the manager of each firm prefers scenario IV when the emissions tax rate is low, whereas he or she prefers scenario VII when the emissions tax rate is high. According to Proposition 5, the owners of each firm always choose cooperative ECSR. This means that when the tax rate is high, the interests of owners and managers are coincident, but conversely, when the tax rate is low, the interests of owners and managers are in conflict. This paper also shows that managers always prefer ERJV regardless of the presence or absence of coordination in ECSR and environmental R&D. The reason why managers prefer scenario IV when the tax rate is low is that net profit increases because of the greatly expanding output level while also making some environmental R&D investments in a regulatory circumstance where emission tax payments are smaller. Conversely, the reason why managers prefer scenario VII when the tax rate is high is that pollution emissions in scenario VII become the smallest among the eight scenarios because the output is smaller, although environmental R&D is implemented to some extent. Reducing pollution results in a smaller degree of environmental damage and, at the same time, significantly lower tax payments. These effects result in greater remuneration for the manager in scenario VII.

Proposition 6, as in the analysis by Xing and Lee (2023), indicates that a conflict of interest between managers and shareholders can occur, whereas Proposition 5 plays a key role in determining which scenario is realized. From Proposition 5, each manager selects R&D formation among scenarios V-VIII and determines its own abatement level at stage 2. Section 5 provides further discussion of this topic.

Before proceeding to the discussion in Section 5, we compare the social welfare of the eight scenarios under a given emissions tax rate. Hereinafter, for simplicity, we make the following assumption:

Assumption 2. $A = 100$.

Because of Assumptions 1 and 2, we proceed with the analysis under $0 \leq t < 20$. Social welfare under scenarios I, II, V, and VI is always lower than under the other scenarios regardless of the degrees of technological spillover, environmental damage, and the emissions tax rate (see Appendix J). Thus, the scenario that yields the greatest social welfare among the eight scenarios is summarized in the (t, d)-plane (Figure 1). Figure 1 shows that, given an emissions tax rate t, as the value of d increases, the socially desirable scenario changes in the order of scenarios III, IV, VIII, and VII. In all four of these scenarios, an ERJV is formed.

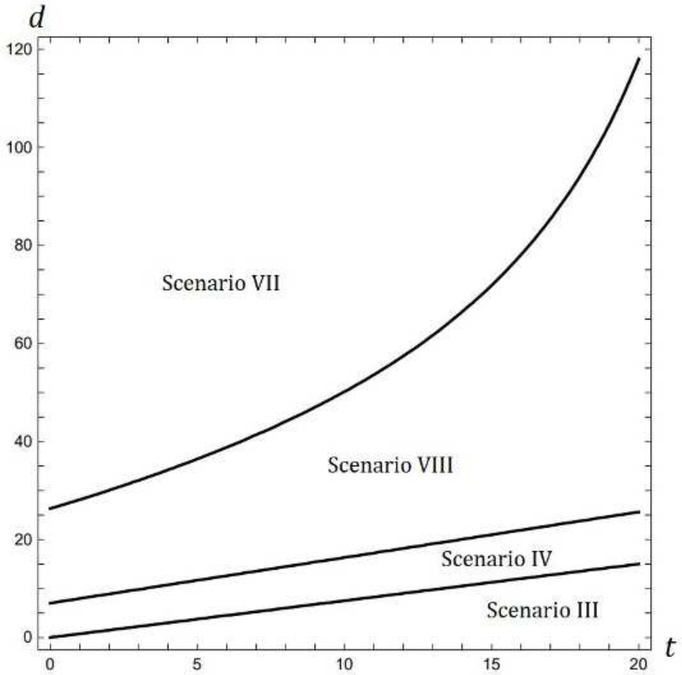

Figure 1: Socially preferable scenario.

Figure 1 indicates that when the damage parameter d is low enough, ERJV competition/cooperation under noncooperative ECSR (scenarios III and IV) yields the highest social welfare among the eight scenarios. Thus, cooperative ECSR is not always socially beneficial. The intuition behind this result can be explained as follows. An important factor is the degree of environmental damage. Noncooperative ECSR increases output (consumer surplus) and also increases both the amount of pollution and tax revenues (tax payments). In addition, full sharing of technological information through the ERJV results in lower R&D investment costs, which generates an increase in the level of environmental R&D investment and a decrease in tax payments. As a result, some increase in profit arises. When the damage coefficient d is small, the sum of consumer surplus, tax revenue, and net profit increases, whereas the degree of environmental damage is smaller. Therefore, when d is sufficiently small, scenario III is socially superior because the sum of the surplus from the good market and tax revenues becomes larger, although the amount of pollution is relatively large. Furthermore, as the degree of d gradually increases, in scenario IV, tax revenues decline, while profits from the good market increase and environmental damage decreases. The effects of increased profits and decreased environmental damage dominate the effect of decreased tax revenues, which results in a more socially superior scenario IV than scenario III.

When the damage parameter d becomes greater further, social superiority appears in the case of cooperative ECSR. From Proposition 3 and Appendix G, cooperative ECSR yields decreasing effects on production (consumer surplus) and pollution. In addition, when d is large, the diminishing effect of environmental damage resulting from pollution abatement becomes greater. Therefore, when the degree of d is large, social superiority lays in the scenario in which environmental damage is smaller. Scenario VIII results in a smaller summation of consumer surplus, tax revenues, and net profits than scenario IV, whereas environmental damage is greatly decreased. Consequently, as the damage coefficient d increases, scenario VIII has social superiority over scenario IV. As the value of d becomes greater further, social superiority appears in scenario VII. The consumer surplus and tax revenues in scenario VII are the smallest among the eight scenarios. However, among the eight scenarios, scenario VII has the greatest net profit and the least amount of environmental damage. Small amounts of environmental damage are the determinant factor in increasing social welfare, resulting in scenario VII having the highest social welfare among the eight scenarios when d is large enough.

From the results of the social welfare comparisons, we obtain important implications for competition policy. The implications are summarized in Proposition 7.

Proposition 7. *Given an emissions tax rate, antitrust authorities should always allow the formation of an ERJV regardless of the degree of technological spillover and environmental damage.*

The rate of environmental pollution tax is determined at the initiative of the government environmental authorities of the country.[19] However, the guidelines for determining whether RJV is allowable are enacted by government antitrust authorities.[20] In other words, multiple departments of regulatory decision-making exist within the government. One feature can be noted here. The emission tax rate does not change very frequently. Therefore, we can regard as plausible, at least in the short term, a situation in which the government antitrust authorities decide whether ERJV is allowable with the emission tax rate as a given. Our game model has important implications for real-world regulatory environments. As Proposition 7 indicates, when tax rates are given, a strong policy implication is that ERJV should always be allowed regardless of the degree of environmental damage and technological spillover. However, decision-making on whether the coordination of environmental R&D effort levels should be allowed depends on the value of the damage coefficient d.

Next, from the viewpoint of consumers, we investigate the ranking of the net consumer surplus (NCS), defined as consumer surplus minus environmental damage: $NCS \equiv CS - D(E)$. Each NCS under scenarios I, II, III, V, and VI is invariably smaller than those under the other scenarios regardless of the degree of technological spillover and environmental damage (see Appendix K). As a result, the scenario that generates the greatest NCS among the eight scenarios is summarized in Figure 2. Figure 2 indicates that, given an emissions tax rate, the greatest NCS changes in the order of scenarios IV, VIII, and VII as the value of d increases. The intuition for this result is as follows. The key is the degree of d. As shown in Proposition 3, noncooperative ECSR increases consumer surplus (output). Furthermore, an increase in output results in greater amounts of pollution. Then, the perfect sharing of technical information through ERJV leads to lower R&D investment costs, which enhances the degree of environmental R&D effort. Indeed, among scenarios I, II, III, and IV, Scenario IV yields the greatest emission abatement (see Appendix E). Furthermore, among the eight scenarios, scenarios I, II, III, and IV yield the highest consumer surplus (Proposition 3), whereas the pollution under scenario IV is the lowest among scenarios I, II, III, and IV (Appendix G). Therefore, when d is small, the consumer surplus, CS, is much greater than the environmental damage. For this reason, when the value of d is small, the value of NCS under scenario IV becomes the largest among the eight scenarios.

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[19] For example, the Environmental Protection Agency in the U.S. and the Ministry of the Environment in Japan play this role.
[20] For example, the Japan Fair Trade Commission and the Australia Competition & Consumer Commission play this role.

When d is moderate or relatively large, the value of NCS becomes larger in the case of cooperative ECSR. As shown in Proposition 3 and Appendix G, cooperative ECSR has a decreasing effect on output (CS) and pollution emissions. Moreover, when d is large, the effect of reducing environmental damage through pollution reduction becomes considerably greater. Thus, when the degree of d is moderate or relatively large, the scenario that generates small environmental damage results in a greater net consumer surplus. Firms' emission abatement efforts have a significant effect on environmental damage. In fact, Scenarios 7 and 8 yield greater pollution abatements (Appendix E). As shown in Figure 2, when the value of d is moderate or relatively large, NCS under scenario VIII becomes the largest among the eight scenarios. Then, CS under scenario VIII becomes smaller than that under scenario IV (see Proposition 3). In contrast, pollution emissions under scenario VIII are greatly reduced, resulting in considerably less environmental damage. Therefore, as d increases, scenario VIII results in a larger NCS than does scenario IV. In addition, as the value of d increases further, scenario VII yields the largest NCS instead of scenario VIII. The consumer surplus (output) under scenario VII is the smallest among the eight scenarios (Proposition 3). Moreover, the environmental damage under scenario VII is the smallest among the eight scenarios (Proposition 4). Smaller amounts of environmental damage are the determining factor of increasing NCS. Consequently, when d is sufficiently large, Scenario VII yields the greatest NCS among the eight scenarios.

In Figure 2, which represents the scenario yielding the greatest NCS, we should note that the ERJV is formed in all three of these scenarios. This result complements Proposition 7. That is, Figures 1 and 2 state that ERJV should always be allowable regardless of whether antitrust authorities adopt net consumer surplus or social welfare as the welfare criterion.

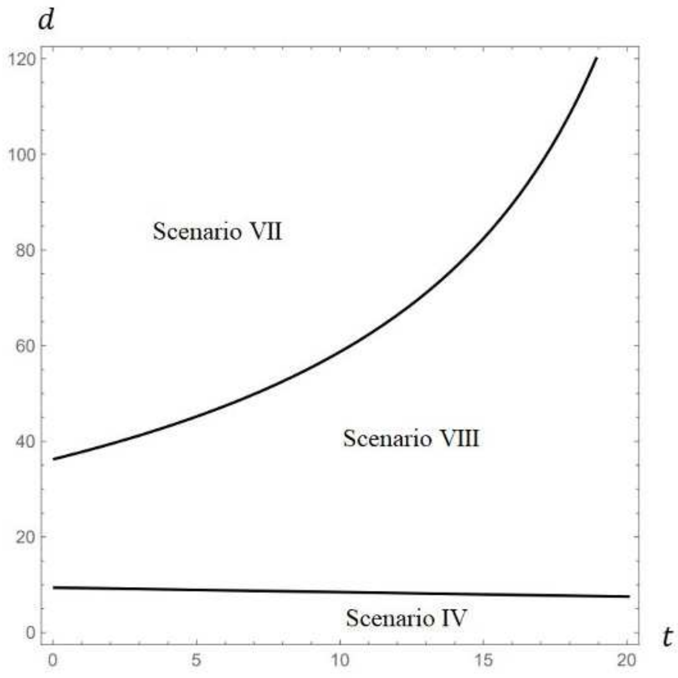

Figure 2: Comparison of net consumer surplus.

In industries such as oil refining, chemicals, and steel, firms emit nitrogen oxides (NO_x), sulphur oxides (SO_x), and carbon dioxides (CO_2). Flue gas desulfurization equipment and denitrification equipment are examples of emission reducing equipment installed in the plants of such industries. CO_2 has a global warming effect but does not cause any direct health hazard to the human body. However, SO_x and NO_x are harmful to human health (e.g., OECD (2013, pp.26-29)). The value of d expresses how significantly society considers the environmental damage caused by such pollutants. Thus, the value of d becomes greater if severe health problems are realized because of the higher content of SO_x and NO_x in pollution emissions or if the damage caused by global warming is considerably more severe. The results of this section suggest that the value of d should be carefully evaluated when designing policies since the preferred scenario varies with the coefficient of environmental damage.

5. Conflicts of interest and choices between owners and managers

According to Propositions 5 and 6, owners and managers have conflicting interests. The owners of each firm choose whether they cooperate or compete regarding the decision-making of the degree of ECSR before stage 1. In contrast, the manager of each firm chooses one R&D formation from among the four alternatives at stage 2. Table 2 provides the payoff matrix resulting from their choices.

Table 2: Payoff matrix and choices between owners and managers

		Manager i			
		Noncooperative environmental R&D	Cooperative environmental R&D	ERJV competition	ERJV cooperation
Owner i	Noncooperative ECSR	$(\pi^{\mathrm{I}}, V^{\mathrm{I}})$	$(\pi^{\mathrm{II}}, V^{\mathrm{II}})$	$(\pi^{\mathrm{III}}, V^{\mathrm{III}})$	$(\pi^{\mathrm{IV}}, V^{\mathrm{IV}})$
	Cooperative ECSR	$(\pi^{\mathrm{V}}, V^{\mathrm{V}})$	$(\pi^{\mathrm{VI}}, V^{\mathrm{VI}})$	$(\pi^{\mathrm{VII}}, V^{\mathrm{VII}})$	$(\pi^{\mathrm{VIII}}, V^{\mathrm{VIII}})$

Here, we explicitly set stage 0 before stage 1. We assume that at stage 0, the owners of each firm choose to cooperate or compete in determining the degree of ECSR. Proposition 5 shows that at stage 0, the owners of each firm always choose cooperative ECSR, which is the dominant strategy. This finding is consistent with the results of Xing and Lee (2023). However, our analysis differs from the results of Xing and Lee (2023, Section 4.2). We find from Proposition 6 that the manager of each firm prefers ERJV cooperation (scenario IV) when the emissions tax rate is low, whereas he or she does ERJV competition (scenario VII) when the emissions tax rate is high. Therefore, at stage 2, each manager selects environmental R&D formation from among scenarios V-VIII.

According to (I.12) and (I.13) in Appendix I, the values of V^{V} and V^{VI} are less than those in the other scenario. In addition, we have already obtained $V^{\mathrm{VIII}} \geq V^{\mathrm{VII}}$ for all $t \in (0, 3(-125 + 92\sqrt{5})A/1405]$ and $\delta \in [0,1)$ and $V^{\mathrm{VII}} > V^{\mathrm{VIII}}$ for all $t \in (3(-125 + 92\sqrt{5})A/1405, A/5)$ and $\delta \in [0,1)$ (see Appendix I). Thus, we have the following result:

Proposition 8. *The equilibrium is* (π^{VIII}, V^{VIII}) *if the emissions tax rate* t *is low. Conversely, the equilibrium is* (π^{VII}, V^{VII}) *if the emissions tax rate* t *is high.*

Consequently, when $t < 3(-125 + 92\sqrt{5})A/1405$, manager i chooses ERJV cooperation at stage 2. On the other hand, when $3(-125 + 92\sqrt{5})A/1405 < t < A/5$, manager i chooses ERJV competition at stage 2.

6. Further discussion: optimal emissions taxation

In this section, on the basis of the discussions in Section 5, we examine the optimal emissions taxation before stage 0. Here, the stage of the government's pollution emission taxation is referred to as stage G. In this extended analysis, we consider the timing of the following game:

Stage G: The government environmental authorities determine the emissions tax rate t to maximize social welfare.

Stage 0: The owners of each firm choose to cooperate or compete in determining the degree of ECSR.

Stage 1: The owners of each firm choose the level of θ_i to maximize their own profit π_i or joint profits $(\pi_i + \pi_j)$.

Stage 2: Manager i chooses one of the following four R&D formations: noncooperative environmental R&D, cooperative environmental R&D, ERJV competition, or ERJV cooperation. Moreover, manager i determines the level of emission abatement effort z_i to maximize V_i.

Stage 3: Manager i determines the output level q_i to maximize V_i.

6.1 Analysis of Stage G

Section 5 completes the analysis of stage 0. Therefore, in this subsection, we concentrate on the analysis of stage G. In stage G, the government environmental authorities determine the emissions tax rate t to maximize social welfare. Hereinafter, to ensure that the equilibrium values of the CSR level, environmental R&D effort level, output level and pollution level for each scenario are not negative (*i.e.*, in Tables A2(I)-(VIII) in Appendix L, $\hat{\theta}^{\mathrm{h}} \geq 0, \hat{z}^{\mathrm{h}} > 0, \hat{q}^{\mathrm{h}} > 0, \hat{e}^{\mathrm{h}} > 0, (\mathrm{h} = \mathrm{I, II, III, IV, V, VI, VII, VIII})$), we establish Assumption 3.

Assumption 3. $\frac{50}{3} < d < \frac{125}{4}$.

Assumption 3 indicates that society's evaluation of environmental damage is not too slight and, at the same time, not too serious. From the first-order conditions for the maximization of social welfare derived in Tables A1(I)-(VIII) in Appendix B, the optimal emissions tax rate for each scenario is derived as follows.[21] The sufficient conditions for a positive value of the emissions tax rate vary for each scenario (see footnote 22 and Eqs. (29)-(32)).[22]

$$\hat{t}^{\mathrm{I}} = \frac{(3d(6-\delta) - 100(3-\delta))(3-\delta)}{45 - 30\delta + 2\delta^2}, \tag{25}$$

$$\hat{t}^{\mathrm{II}} = \frac{6d(3-\delta) - 100(3-2\delta)}{15 - 4\delta}, \tag{26}$$

$$\hat{t}^{\mathrm{III}} = \frac{10(3d-40)}{17}, \tag{27}$$

$$\hat{t}^{\mathrm{IV}} = \frac{4(3d-25)}{11}, \tag{28}$$

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[21] A "hat" means the optimal emissions tax rate obtained as extended equilibrium outcome. The subscript "0" indicates that optimal emissions tax rate is determined to be 0, and the subscript "P" denotes that the sign of the optimal emissions tax rate is determined to be positive.

[22] If $d > 50/3$, then $\hat{t}^{\mathrm{I}} > 0, \hat{t}^{\mathrm{II}} > 0, \hat{t}^{\mathrm{III}} > 0$, and $\hat{t}^{\mathrm{IV}} > 0$ for all $\delta \in [0,1]$.

$$\hat{t}^{\mathrm{V}}=\begin{cases}\hat{t}_0^{\mathrm{V}}=0 \quad if\ \dfrac{50}{3}< d\leq\dfrac{200}{7}\\ \hat{t}_{\mathrm{P}}^{\mathrm{V}}=\dfrac{d(6-\delta)(63-42\delta+4\delta^2)-200(3-\delta)(18-12\delta+\delta^2)}{(6-\delta)(45-30\delta+2\delta^2)} \quad if\ \dfrac{200}{7}<d<\dfrac{125}{4},\end{cases} \tag{29}$$

$$\hat{t}^{\mathrm{VI}}=\begin{cases}\hat{t}_0^{\mathrm{VI}}=0 \ \ if\ \dfrac{50}{3}< d\leq\dfrac{1475}{58}\\ \hat{t}_{\mathrm{P}}^{\mathrm{VI}}=\dfrac{4(d(6-\delta)(87-40\delta+4\delta^2)-25(3-2\delta)(177-52\delta+4\delta^2))}{1557-798\delta+140\delta^2-8\delta^3} \quad if\ \dfrac{1475}{58}<d<\dfrac{125}{4},\end{cases} \tag{30}$$

$$\hat{t}^{\mathrm{VII}}=\begin{cases}\hat{t}_0^{\mathrm{VII}}=0 \quad if\ \dfrac{50}{3}<d\leq\dfrac{112}{5}\\ \hat{t}_{\mathrm{P}}^{\mathrm{VII}}=\dfrac{5(5d-112)}{17} \quad if\ \dfrac{112}{5}<d<\dfrac{125}{4},\end{cases} \tag{31}$$

$$\hat{t}^{\mathrm{VIII}}=\begin{cases}\hat{t}_0^{\mathrm{VIII}}=0 \quad if\ \dfrac{50}{3}<d\leq\dfrac{215}{17}\\ \hat{t}_{\mathrm{P}}^{\mathrm{VIII}}=\dfrac{20(17d-215)}{297} \quad if\ \dfrac{215}{17}<d<\dfrac{125}{4}.\end{cases} \tag{32}$$

On the basis of these tax rates (25)-(32), the equilibrium values (Expanded SPNE outcomes) for the other economic variables in each scenario are obtained as shown in Tables A2(I)-(VIII) in Appendix L.

The investigations of social welfare in Section 4 show that under a given tax rate, the values of social welfare in scenarios I, II, V, and VI are lower than those in the other scenarios (*i.e.*, scenarios III, IV, VII, and VIII) (see Figure 1 and Appendix J). Therefore, the government environmental authorities do not actually impose the optimal emissions tax rates for scenarios I, II, V, and VI at stage G. Furthermore, from Propositions 5 and 8, if $t<t_{\mathrm{C}}\equiv 300(-125+92\sqrt{5})/1405$ (≈ 17.2352) under Assumption 2, then manager i chooses ERJV cooperation at stage 2. On the other hand, if $t_{\mathrm{C}}<t<20$, then manager i chooses ERJV competition at stage 2.

Thus, hereinafter, we concentrate on scenarios VII and VIII.

6.2 Strategic manipulation of the emissions tax rate

We now investigate the relationships among the three tax rates, $\hat{t}_{\mathrm{P}}^{\mathrm{VII}}$, $\hat{t}_{\mathrm{P}}^{\mathrm{VIII}}$, and t_{C}, focusing on the two tax rates, $\hat{t}_{\mathrm{P}}^{\mathrm{VII}}$ and $\hat{t}_{\mathrm{P}}^{\mathrm{VIII}}$, derived in (31) and (32), and the tax rate t_{C}, which is the critical point at which the manager chooses ERJV cooperation or ERJV competition. The results of the comparisons are as follows:

$$\hat{t}_{\mathrm{P}}^{\mathrm{VII}}=\tfrac{5(5d-112)}{17}<\hat{t}_{\mathrm{P}}^{\mathrm{VIII}}=\tfrac{20(17d-215)}{297} \text{ for all } \tfrac{50}{3}<d<\tfrac{125}{4}, \tag{33}$$

$$\hat{t}_{\mathrm{P}}^{\mathrm{VII}}<t_{\mathrm{C}}(\equiv 300(-125+92\sqrt{5})/1405) \text{ for all } \tfrac{50}{3}<d<\tfrac{125}{4}, \tag{34}$$

$$\hat{t}_{\mathrm{P}}^{\mathrm{VIII}}\leq t_{\mathrm{C}} \text{ if } \tfrac{50}{3}<d\leq d_{\mathrm{C}}\equiv\tfrac{4(-12740+20493\sqrt{5})}{4777}, \tag{35}$$

$$\hat{t}_{\mathrm{P}}^{\mathrm{VIII}}>t_{\mathrm{C}} \text{ if } d_{\mathrm{C}}\equiv\tfrac{4(-12740+20493\sqrt{5})}{4777}<d<\tfrac{125}{4}. \tag{36}$$

Here, we provide preliminaries for the discussion of social welfare. From Table A2(VII-VIII), we have

$$\widehat{W}_{\mathrm{P}}^{\mathrm{VIII}}=\frac{1}{198}(910000-18200d+289d^2)>\widehat{W}_{\mathrm{P}}^{\mathrm{VII}}=\frac{25}{17}(3200-72d+d^2), \tag{37}$$

$$\widehat{W}_{\mathrm{P}}^{\mathrm{VIII}}=\frac{1}{198}(910000-18200d+289d^2)>\widehat{W}_0^{\mathrm{VIII}}=\frac{5}{2}(1745-22d) \tag{38}$$

for all $d \in (50/3, 125/4)$. Next, when $50/3 < d \leq 112/5$, we have straightforwardly that $t_{\mathrm{C}} > \hat{t}_{\mathrm{P}}^{\mathrm{VIII}} > \hat{t}^{\mathrm{VII}}(= \hat{t}_0^{\mathrm{VII}}) = 0$. After manipulation, we obtain the following:

$$\widehat{W}_{\mathrm{P}}^{\mathrm{VIII}} > \widehat{W}_0^{\mathrm{VII}} = 3968 - 40d > \widehat{W}_{\mathrm{P}}^{\mathrm{VII}}(\hat{t}_{\mathrm{P}}^{\mathrm{VIII}}) = \frac{8(49331774 - 1077268d + 15419d^2)}{88209} \tag{39}$$

for all $d \in (50/3, 112/5]$. Here, $\widehat{W}_{\mathrm{P}}^{\mathrm{VII}}(\hat{t}_{\mathrm{P}}^{\mathrm{VIII}})$ is the equilibrium value of social welfare when the government environmental authorities determine $\hat{t}_{\mathrm{P}}^{\mathrm{VIII}}$ at stage G and then the manager chooses ERJV cooperation at stage 2.

Moreover, when $\frac{112}{5} < d \leq d_{\mathrm{C}} \equiv \frac{4(-12740+20493\sqrt{5})}{4777} (\approx 27.7025)$, then $t_{\mathrm{C}} \geq \hat{t}_{\mathrm{P}}^{\mathrm{VIII}} > \hat{t}_{\mathrm{P}}^{\mathrm{VII}} > 0$. The value of d_{C} is defined as d satisfying $\widehat{W}_{\mathrm{P}}^{\mathrm{VIII}} = \widehat{W}^{\mathrm{VIII}}(t_{\mathrm{C}})$ (see Figure 3). We define $\widehat{W}^{\mathrm{VIII}}(t_{\mathrm{C}})$ as the equilibrium value of social welfare when the government environmental authorities set t_{C} at stage G and then the manager chooses ERJV cooperation at stage 2. The value of $\widehat{W}^{\mathrm{VIII}}(t_{\mathrm{C}})$ is derived as

$$\widehat{W}^{\mathrm{VIII}}(t_{\mathrm{C}}) = \frac{4\left(20(2251297 + 527436\sqrt{5}) + 281(-8645 + 3519\sqrt{5})d\right)}{78961}. \tag{40}$$

Then, we have

$$\widehat{W}_{\mathrm{P}}^{\mathrm{VIII}} \geq \widehat{W}^{\mathrm{VIII}}(t_{\mathrm{C}}) > \widehat{W}_{\mathrm{P}}^{\mathrm{VIII}}(\hat{t}_{\mathrm{P}}^{\mathrm{VII}}) = \frac{38992336 - 726152d + 12405d^2}{9248} > \widehat{W}_{\mathrm{P}}^{\mathrm{VII}}(\hat{t}_{\mathrm{P}}^{\mathrm{VIII}}) \tag{41}$$

for all $d \in (112/5, d_{\mathrm{C}}]$. Therein, $\widehat{W}_{\mathrm{P}}^{\mathrm{VIII}}(\hat{t}_{\mathrm{P}}^{\mathrm{VII}})$ is the equilibrium value of social welfare when the government environmental authorities set $\hat{t}_{\mathrm{P}}^{\mathrm{VII}}$ at stage G and then the manager chooses ERJV competition at stage 2.

Finally, when $d_{\mathrm{C}} < d < 125/4$, then $\hat{t}_{\mathrm{P}}^{\mathrm{VIII}} > t_{\mathrm{C}} > \hat{t}_{\mathrm{P}}^{\mathrm{VII}} > 0$. Therefore, the value of $\widehat{W}_{\mathrm{P}}^{\mathrm{VIII}}$ is not realized because ERJV cooperation is not selected at stage 2. Then, we have

$$\widehat{W}^{\mathrm{VIII}}(t_{\mathrm{C}}) > \widehat{W}_{\mathrm{P}}^{\mathrm{VIII}}(\hat{t}_{\mathrm{P}}^{\mathrm{VII}}) > \widehat{W}_{\mathrm{P}}^{\mathrm{VII}}(\hat{t}_{\mathrm{P}}^{\mathrm{VIII}}) \tag{42}$$

for all $d \in (d_{\mathrm{C}}, 125/4)$. From these results, we find that the value of $\widehat{W}_{\mathrm{P}}^{\mathrm{VII}}(\hat{t}_{\mathrm{P}}^{\mathrm{VIII}})$ is always smaller than $\widehat{W}^{\mathrm{VIII}}(t_{\mathrm{C}})$. Furthermore, government environmental authorities invariably have social incentives for setting $\hat{t}_{\mathrm{P}}^{\mathrm{VIII}}$.

If $\frac{50}{3} < d \leq d_{\mathrm{C}} \equiv \frac{4(-12740+20493\sqrt{5})}{4777} (\approx 27.7025)$, then the government environmental authorities determine the emissions tax rate $\hat{t}_{\mathrm{P}}^{\mathrm{VIII}}$ at stage G, and each manager chooses ERJV cooperation because $\hat{t}_{\mathrm{P}}^{\mathrm{VIII}} < t_{\mathrm{C}}$. That choice of each manager is consistent with the R&D formation preferred by the government antitrust authorities, who are social welfare maximizers. However, if $d_{\mathrm{C}} < d < 125/4$, then the manager chooses ERJV competition because $\hat{t}_{\mathrm{P}}^{\mathrm{VIII}} > t_{\mathrm{C}}$. That choice of each manager is not consistent with the R&D formation preferred by the government antitrust authorities. Namely, a conflict of interest occurs between the government antitrust authorities and the manager. If the managers of the two firms both choose ERJV competition after the emissions tax rate is determined, then social welfare decreases relative to the case where ERJV cooperation is chosen by the managers. That is, when $d_{\mathrm{C}} < d < 125/4$, if the government environmental authorities impose $\hat{t}_{\mathrm{P}}^{\mathrm{VIII}}$, the optimality of the taxation is compromised. In other words, the time-inconsistency problem of taxation arises.

To avoid the time-inconsistency problem of emissions taxation, government environmental authorities can choose the tax rate $\hat{t}_{\mathrm{P}}^{\mathrm{VII}}$ as the second-best tax rate. Here, from (34), we have $\hat{t}_{\mathrm{P}}^{\mathrm{VII}} < t_{\mathrm{C}}$ for all $50/3 < d <$

$125/4$. Therefore, if the government environmental authorities impose $\hat{t}_{\mathrm{P}}^{\mathrm{VII}}$ at stage G, the manager chooses ERJV cooperation at stage 2. However, the social welfare $\widehat{W}^{\mathrm{VIII}}(\hat{t}_{\mathrm{P}}^{\mathrm{VII}})$ is then less than $\widehat{W}_{\mathrm{P}}^{\mathrm{VIII}}$.

When $d_{\mathrm{C}} < d < 125/4$, there is an alternative for the government environmental authorities other than imposing $\hat{t}_{\mathrm{P}}^{\mathrm{VII}}$. That is, strategic manipulation of the emissions tax rate incentivizes each manager to choose ERJV cooperation and consequently prevents, as much as possible, the lowering of social welfare. The taxation is to set the critical tax rate t_{C} and incentivize each manager to choose ERJV cooperation. However, for such strategic manipulation to be socially justified, it is necessary that $\widehat{W}^{\mathrm{VIII}}(t_{\mathrm{C}}) > \widehat{W}^{\mathrm{VIII}}(\hat{t}_{\mathrm{P}}^{\mathrm{VII}})$ is satisfied. Consequently, from (42) and Figure 3, we have $\widehat{W}^{\mathrm{VIII}}(t_{\mathrm{C}}) > \widehat{W}^{\mathrm{VIII}}(\hat{t}_{\mathrm{P}}^{\mathrm{VII}})$ for all $d \in (d_{\mathrm{C}}, 125/4)$.

Thus, the optimal taxation of government environmental authorities can be summarized as follows. If $50/3 < d \le d_{\mathrm{C}}$, the government environmental authorities choose $\hat{t}_{\mathrm{P}}^{\mathrm{VIII}}$; conversely, if $d_{\mathrm{C}} < d < 125/4$, the government environmental authorities impose t_{C} to make the manager choose ERJV cooperation. Furthermore, government antitrust authorities should allow ERJV cooperation regardless of the value of the environmental damage coefficient d. Then, in the market, the owners of each firm exhibit cooperative behavior at the stage of choosing the degree of ECSR, and the manager selects ERJV cooperation at stage 2.

Thus, the following proposition is obtained.

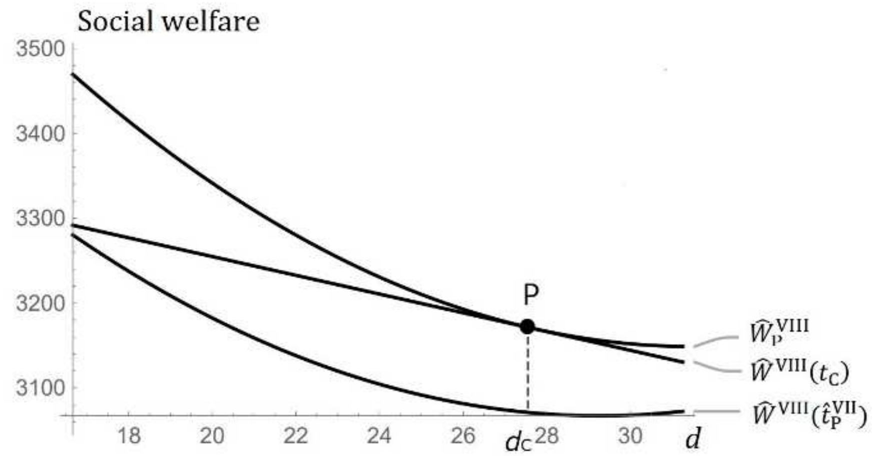

Figure 3: Social welfare

Proposition 9. *Suppose that both the government's environmental and antitrust authorities simultaneously determine the emissions tax rate and ERJV policy for ECSR firms. If the damage coefficient is not large (i.e., $d \le d_C$), government environmental authorities should impose $\hat{t}_P^{VIII}$ at stage G. Conversely, if the damage coefficient is large (i.e., $d > d_C$), government environmental authorities should impose t_C at stage G. In addition, government antitrust authorities should allow ERJV cooperation regardless of the value of the coefficient of environmental damage, d.*

Proposition 9 indicates how two government authorities should align their emission taxation and ERJV policies. Proposition 9 also shows that strategic pollution taxation, which incentivizes each manager to choose ECSR cooperation, is socially beneficial. This is because if $d > d_C$, the government environmental authorities set the minimum emissions tax rate, t_{C}, such that the manager has a private incentive to choose

ERJV cooperation. This strategic manipulation not only softens the time inconsistency problem of pollution taxation but is also one of the theoretical contributions of this paper to environmental R&D studies. In addition, this paper contributes to competition policy. The analysis in this paper provides a policy recommendation that the ERJV should be allowed regardless of whether the government antitrust authorities decide to allow or disallow the ERJV at the same time as or after the emission tax rate is determined. This policy recommendation is significant in the current oligopoly market, where ECSRs are widespread. Whether ERJVs should be allowed in oligopolistic markets is one of the most important issues with respect to competition policy. This paper provides a new policy recommendation from a theoretical perspective for competition policy for ECSR firms.

This paper provides further suggestions from a different perspective. This paper employs a strategic delegation model in which the owners delegate management rights to a manager who adopts ESCR behavior. Importantly, the government's ability to observe managers' remuneration contracts or whether managers' remuneration contracts are open to the public is an indispensable factor in policy-making. If the disclosure or observability of managers' remuneration contracts were absent, the argument of this paper would fail. Currently, there is a growing trend of enforcing disclosure requirements for managers' remuneration.[23] In the United States, the Securities and Exchange Commission (SEC) has mandated the disclosure of detailed information on executive compensation levels, composition, determining factors, etc. (e.g., see Gipper (2021) and Murphy (2013)).[24] Such detailed disclosure of compensation information is required by the German Stock Corporation Act, as well as by the SEC.[25] In contrast, in Japan, disclosure of information on compensation contracts for executives with total compensation of 100 million yen or more has been required by the Cabinet Office Order on Disclosure of Corporate Affairs since 2019. This indicates that the level of regulation in Japan is quite loose and that the Japanese government is reluctant to disclose detailed information. Relatedly, this paper demonstrates from a theoretical perspective that the disclosure of remuneration contracts is also necessary for decision-making concerning the emissions tax rate and environmental R&D policy.

7. Conclusion

In this paper, we consider both the rule of when ERJV is socially allowable and the optimal emission taxation, assuming a situation in which the government imposes a pollution emission tax on a Cournot duopoly market consisting of two ECSR firms whose owners delegate managerial decision-making rights to managers who adopt ECSR behavior. Unlike the R&D spillover assumption used in previous environmental R&D models, we employ the new model of Macho-Stadler et al. (2021), which overcomes the limitations of previous studies.

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[23] For example, see Ciesla et al. (2021).

[24] As an example, each director's compensation of Apple Inc. is disclosed on the proxy statement for Annual Meeting of Shareholders. For the proxy statement for 2024, see the following website. URL: https://www.sec.gov/Archives/edgar/data/320193/000130817924000010/laapl2024_def14a.pdf (Last accessed: June 23, 2024)

[25] As an example, the compensation of Siemens Energy's Executive Board is disclosed on the following website. URL: https://www.siemens-energy.com/global/en/home/investor-relations/corporate-governance/executive-board-compensation.html (Last accessed: June 23, 2024)

As a result, this paper provides three contributions. First, our investigation reveals that strategic manipulation of the emissions tax rate, which incentivizes managers to choose ECSR cooperation, is effective in mitigating the decline in social welfare. The second contribution relates to competition policy. The policy recommendation we derive is that government antitrust authorities should always allow the ERJV. Moreover, it is valid regardless of the timing of the decision-making of government antitrust authorities on whether ERJVs should be allowed, that is, whether the decision-making of government antitrust authorities is made at the same time as or after the emissions tax rate is determined. The third contribution is to clarify that the assumption of disclosure (or observability) of managers' remuneration contracts should be realized socially. In other words, the disclosure (or observability) of managers' remuneration contracts should be encouraged. This strongly suggests that in oligopolistic markets where ECSRs are widespread, designing socially desirable policies requires not only information on R&D costs and the degree of environmental damage but also information on firms' internal contracts.

Two directions for possible extension are as follows. First, a comparison should be made with the case of price competition in the market. Second, it would be interesting to analyze market competition by asymmetric ECSR firms. These extensions warrant future research.

References

d'Aspremont, C. and Jacquemin, A. (1988). Cooperative and noncooperative R&D in duopoly with spillovers. *American Economic Review*, *78*(5), 1133-1137.

Bárcena-Ruiz, J. C., Garzón, M. B., and Sagasta, A. (2023). Environmental corporate social responsibility, R&D and disclosure of "green" innovation knowledge. *Energy Economics*, *120*, 106628.

Buccella, D., Fanti, L., and Gori, L. (2021). To abate, or not to abate? A strategic approach on green production in Cournot and Bertrand duopolies. *Energy Economics, 96*, 105164.

Buccella, D., Fanti, L., and Gori, L. (2022). 'Green' managerial delegation theory. *Environment and Development Economics*, *27*(3), 223-249.

Buccella, D., Fanti, L., and Gori, L. (2023). Environmental delegation versus sales delegation: A game-theoretic analysis. *Environment and Development Economics*, *28*(5), 469-485.

Cabon-Dhersin, M. L. and Raffin, N. (2024). Cooperation in green R&D and environmental policies: Taxes versus standards. *Journal of Regulatory Economics* (In Press). DOI: https://doi.org/10.1007/s11149-024-09475-4

Chen, J., Sun, C., Shi, J., and Liu, J. (2022). Technology R&D and sharing in carbon emission reduction in a duopoly. *Technological Forecasting and Social Change*, *183*, 121936.

Chiou, J. R. and Hu, J. L. (2001). Environmental research joint ventures under emission taxes. *Environmental and Resource Economics*, *20*, 129-146.

Cieslak, K., Hamberg, M., and Vural, D. (2021). Executive compensation disclosure, ownership concentration and dual-class firms: An analysis of Swedish data. *Journal of International Accounting, Auditing and Taxation, 45*, 100429.

Crifo, P. and Forget, V. (2015). The economics of corporate social responsibility: A firm-level perspective survey. *Journal of Economic Surveys*, *29*(1), 112-130.

Fershtman, C. and Judd, K.L. (1987). Equilibrium incentives in oligopoly. *American Economic Review*, *77*(5), 927-940.

Fukuda, K. and Ouchida, Y. (2020). Corporate social responsibility (CSR) and the environment: Does CSR increase emissions? *Energy Economics*, *92*, 104933.

Gersbach, H. and Requate, T. (2004). Emission taxes and optimal refunding schemes. *Journal of Public Economics, 88*(3-4), 713-725.

Gipper, B. (2021). The economic effects of expanded compensation disclosures. *Journal of Accounting and Economics*, *71*(1), 101338.

Haruna, S. and Goel, R. K. (2019). Optimal pollution control in a mixed oligopoly with research spillovers. *Australian Economic Papers, 58*(1), 21-40.

Hattori, K. (2017). Optimal combination of innovation and environmental policies under technology licensing. *Economic Modelling, 64*, 601-609.

Hirose, K., Lee, S. H., and Matsumura, T. (2020). Noncooperative and cooperative environmental corporate social responsibility. *Journal of Institutional and Theoretical Economics*, *176*(3), 549-571.

Hirose, K. and Matsumura, T. (2022). Common ownership and environmental corporate social responsibility. *Energy Economics, 114*, 106269.

Iannucci, G. and Tampieri, A. (2023). On the evolutionary interplay between environmental CSR and emission tax. *Energy Economics, 128*, 107165.

Kitzmueller, M. and Shimshack, J. (2012). Economic perspectives on corporate social responsibility. *Journal of Economic Literature*, *50*(1), 51-84.

KPMG (2020), *The KPMG Survey of Sustainability Reporting* 2020.
URL: https://assets.kpmg.com/content/dam/kpmg/xx/pdf/2020/11/the-time-has-come.pdf

Lambertini, L. and Tampieri, A. (2015). Incentives, performance and desirability of socially responsible firms in a Cournot oligopoly. *Economic Modelling*, *50*, 40-48.

Lambertini, L. and Tampieri, A. (2023). On the private and social incentives to adopt environmentally and socially responsible practices in a monopoly industry. *Journal of Cleaner Production, 426*, 139036.

Lambertini, L. Poyago-Theotoky, J., and Tampieri, A. (2017). Cournot competition and "green" innovation: An inverted-U relationship. *Energy Economics, 68*, 116-123.

Lyon, T. P. and Maxwell, J. W. (2008). Corporate social responsibility and the environment: A theoretical perspective. *Review of Environmental Economics and Policy*, *2*(2), 240-260.

Macho-Stadler, I., Matsushima, N., and Shinohara, R. (2021). Organizational structure and technological investment. *Journal of Industrial Economics*, *69*(4), 785-816.

Montero, J. P. (2002). Permits, standards, and technology innovation. *Journal of Environmental Economics and Management, 44*(1), 23-44.

Murphy, K. J. (2013). Executive compensation: Where we are, and how we got there. In George M. Constantinides, Milton Harris, and Rene M. Stulz (eds.), *Handbook of the Economics of Finance* (Vol.2, Part A, Chapter 4, pp.211-356). Elsevier.

Nie, P. Y., Wang, C., and Meng, Y. (2019). An analysis of environmental corporate social responsibility. *Managerial and Decision Economics*, *40*(4), 384-393.

OECD (2013), *Environment at a Glance 2013: OECD Indicators*, OECD Publishing.
http://dx.doi.org/10.1787/9789264185715-en

Ouchida, Y. and Goto, D. (2016a). Cournot duopoly and environmental R&D under regulator's precommitment to an emissions tax, *Applied Economics Letters*, *23*(5), 324-331.

Ouchida, Y. and Goto, D. (2016). Environmental research joint ventures and time-consistent emission tax: Endogenous choice of R&D formation. *Economic Modelling*, *55*, 179-188.

Ouchida, Y. and Goto, D. (2022). Strategic non-use of the government's precommitment ability for emissions taxation: Environmental R&D formation in a Cournot duopoly. *Australian Economic Papers*, *61*(1), 181-206.

Pal, R. (2012). Delegation and emission tax in a differentiated oligopoly. *The Manchester School*, *80*(6), 650-670.

Poyago-Theotoky, J. (2007). The organization of R&D and environmental policy. *Journal of Economic Behavior and Organization*, *62*(1), 63-75.

Poyago-Theotoky, J. and Yong, S. K. (2019). Managerial delegation contracts, "green" R&D and emissions taxation, *The B.E. Journal of Theoretical Economics*, *19*(2), 20170128.

Puller, S. L. (2006). The strategic use of innovation to influence regulatory standards. *Journal of Environmental Economics and management, 52*(3), 690-706.

Requate, T. and Unold, W. (2003). Environmental policy incentives to adopt advanced abatement technology: Will the true ranking please stand up? *European Economic Review, 47*(1), 125-146.

Schmitz, J. and Schrader, J. (2015). Corporate social responsibility: A microeconomic review of the literature. *Journal of Economic Surveys*, *29*(1), 27-45.

Sklivas S.D. (1987). The strategic choice of managerial incentives. *RAND Journal of Economics*, *18*, 452–458.

Strandholm, J. C., Espinola-Arredondo, A., and Munoz-Garcia, F. (2018). Regulation, free-riding incentives, and investment in R&D with spillovers. *Resource and Energy Economics*, *53*, 133-146.

Strandholm, J. C., Espinola-Arredondo, A., and Munoz-Garcia, F. (2023). Being green first: Simultaneous vs. sequential abatement decisions. *Economics Letters*, *227*, 111123.

Tomoda, Y. and Ouchida, Y. (2023). Endogenous bifurcation into environmental CSR and non-environmental CSR firms by activist shareholders. *Journal of Environmental Economics and Management*, *122*, 102883.

Vickers, J. (1985). Delegation and the theory of the firm. *Economic Journal, 95*(Supplement), 138-147.

Villena, M. G., and Quinteros, M. J. (2024). Corporate social responsibility, environmental emissions and time-consistent taxation. *Environmental and Resource Economics, 87*(1), 219-255.

Wang, C. (2021). Monopoly with corporate social responsibility, product differentiation, and environmental R&D: Implications for economic, environmental, and social sustainability. *Journal of Cleaner Production*, *287*, 125433.

Xing, M. (2017). The optimal risk choice of cooperative and noncooperative R&D in duopoly with spillovers. *Bulletin of Economic Research, 69*(4), E173-E185.

Xing, M. and Lee, S. H. (2023). Non-cooperative and cooperative environmental R&D under environmental corporate social responsibility with green managerial coordination. *Managerial and Decision Economics*, *44*(5), 2684-2696.

Yong, S. K., Friesen, L., and McDonald, S. (2018). Emission taxes, clean technology cooperation, and product market collusion: Experimental evidence. *Economic Inquiry, 56*(4), 1950-1979.

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Appendix A:

(1) Scenario I: Noncooperative ECSR and noncooperative environmental R&D

In stage 3, manager i noncooperatively determines q_i to maximize the objective function $V_i(q_i, q_j)$. The analysis of stage 3 is identical to that in Subsection 3.1.

In stage 2, manager i noncooperatively chooses the environmental R&D effort level z_i to maximize the objective function:

$$\begin{aligned} V_i(z_i, z_j) = \{A - (q_i(\theta_i, \theta_j) + q_j(\theta_i, \theta_j))\}q_i(\theta_i, \theta_j) - t\{q_i(\theta_i, \theta_j) - z_i\} \\ -\{(\gamma/2)z_i^2 - \delta z_i z_j\} - \theta_i d\{q_i(\theta_i, \theta_j) - z_i + q_j(\theta_i, \theta_j) - z_j\}. \end{aligned} \quad \text{(A.1)}$$

From the corresponding first-order conditions for maximization $\partial V_i(z_i, z_j)/\partial z_i = 0 = \partial V_j(z_i, z_j)/\partial z_j$, the equilibrium R&D effort levels of two firms are derived as

$$z_i(\theta_i, \theta_j) = \frac{d(\gamma\theta_i + \delta\theta_j) + (\gamma + \delta)t}{(\gamma + \delta)(\gamma - \delta)}, \quad \text{(A.2)}$$

$$z_j(\theta_i, \theta_j) = \frac{d(\delta\theta_i + \gamma\theta_j) + (\gamma + \delta)t}{(\gamma + \delta)(\gamma - \delta)}. \quad \text{(A.3)}$$

In stage 1, the owners of firm i noncooperatively choose the level of θ_i to maximize $\pi_i(\theta_i, \theta_j) = \{A - (q_i(\theta_i, \theta_j) + q_j(\theta_i, \theta_j))\}q_i(\theta_i, \theta_j) - t\{q_i(\theta_i, \theta_j) - z_i(\theta_i, \theta_j)\} - \{[z_i(\theta_i, \theta_j)]^2 - \delta z_i(\theta_i, \theta_j)z_j(\theta_i, \theta_j)\}$. We examine the corresponding first-order condition. Then, we have

$$\frac{\partial \pi_i}{\partial \theta_i} = \frac{-dY}{9(\gamma + \delta)^2(\gamma - \delta)^2}, \quad \text{(A.4)}$$

where $Y \equiv \theta_i d\mu_1 + \theta_j d\mu_2 + \mu_3$, $\mu_1 \equiv 4\delta^4 - 18\delta^2\gamma - 8\delta^2\gamma^2 + 9\gamma^3 + 4\gamma^4$, $\mu_2 \equiv \gamma^4 - 2\delta^2\gamma^2 + \delta^4 - 9\delta^3$, $\mu_3 \equiv (9\delta^3 + \delta^4 + 9\delta^2\gamma - 2\delta^2\gamma^2 + \gamma^4)t - A(\gamma^2 - \delta^2)^2$. With respect to the sign of $\mu_i (i = 1,2,3)$, it is straightforward to verify that $\mu_i > 0$: $\mu_1 \equiv 4\delta^4 - 18\delta^2\gamma - 8\delta^2\gamma^2 + 9\gamma^3 + 4\gamma^4 \geq 4\delta^4 - 18\gamma - 8\gamma^2 + 9\gamma^3 + 4\gamma^4 = 4\delta^4 + \gamma(4\gamma + 9)(\gamma^2 - 2) > 0$; $\mu_2 \equiv \gamma^4 - 2\delta^2\gamma^2 + \delta^4 - 9\delta^3 \geq (\gamma^2 - \delta^2)^2 - 9 \geq (\gamma^2 - 1)^2 - 9 > 0$; $\mu_3 \equiv A(\gamma^2 - \delta^2)^2 - (9\delta^3 + \delta^4 + 9\delta^2\gamma - 2\delta^2\gamma^2 + \gamma^4)t > (4(\gamma^2 - \delta^2)^2 - 9\delta^3 - \delta^4 - 9\delta^2\gamma + 2\delta^2\gamma^2 - \gamma^4)t = \left(3(\gamma^2 - \delta^2)^2 - 9\delta^2(\gamma + \delta)\right)t = 3(\gamma + \delta)\left((\gamma + \delta)(\gamma - \delta)^2 - 3\delta^2\right)t > 0$. Thus, we have $Y > 0$. This means that $\partial\pi_i/\partial\theta_i < 0$.

Therefore, the equilibrium ECSR levels are derived as

$$\theta_i^{\mathrm{I}} = 0, \theta_j^{\mathrm{I}} = 0. \quad \text{(A.5)}$$

Equation (A.5) shows that owners do not adopt ECSR in the case of noncooperative ECSR and noncooperative environmental R&D. This result is consistent with the findings of previous studies (Hirose et al.,2020; Xu et al., 2022; Xing and Lee, 2023). By using (A.5), other equilibrium values of the full game are obtained, as shown in Table A1(I).

(2) Scenario II: Noncooperative ECSR and cooperative environmental R&D

In stage 3, manager i noncooperatively determines q_i to maximize the objective function: $V_i(z_i, z_j)$. The analysis of stage 3 is identical to that in Subsection 3.1. In stage 2, manager i cooperatively chooses the environmental R&D effort level z_i to maximize the objective function:

$$\begin{aligned} V_i(z_i,z_j)+V_j(z_i,z_j) = \{&A-(q_i(\theta_i,\theta_j)+q_j(\theta_i,\theta_j))\}q_i(\theta_i,\theta_j)-t\{q_i(\theta_i,\theta_j)-z_i\} \\ &-\{(\gamma/2)z_i^2-\delta z_i z_j\}-\theta_i d\{q_i(\theta_i,\theta_j)-z_i+q_j(\theta_i,\theta_j)-z_j\} \\ &+\{A-(q_i(\theta_i,\theta_j)+q_j(\theta_i,\theta_j))\}q_j(\theta_i,\theta_j)-t\{q_j(\theta_i,\theta_j)-z_j\} \\ &-\{(\gamma/2)z_j^2-\delta z_i z_j\}-\theta_j d\{q_i(\theta_i,\theta_j)-z_i+q_j(\theta_i,\theta_j)-z_j\}. \end{aligned} \tag{A.6}$$

From the corresponding first-order conditions for maximization $\partial(V_i(z_i,z_j)+V_j(z_i,z_j))/\partial z_i = 0 = \partial\,(V_i(z_i,z_j)+V_j(z_i,z_j))/\partial z_j$, the equilibrium R&D effort levels of two firms are derived as

$$z_i(\theta_i,\theta_j) = \frac{d(\theta_i+\theta_j)+t}{\gamma-2\delta}, \tag{A.7}$$

$$z_j(\theta_i,\theta_j) = \frac{d(\theta_i+\theta_j)+t}{\gamma-2\delta}. \tag{A.8}$$

In stage 1, the owners of firm i noncooperatively determine θ_i to maximize its own profit: $\pi_i(\theta_i,\theta_j) = \{A-(q_i(\theta_i,\theta_j)+q_j(\theta_i,\theta_j))\}q_i(\theta_i,\theta_j)-t\{q_i(\theta_i,\theta_j)-z_i(\theta_i,\theta_j)\}-\{[z_i(\theta_i,\theta_j)]^2-\delta z_i(\theta_i,\theta_j)z_j(\theta_i,\theta_j)\}$. The corresponding first-order condition is derived as $\partial\pi_i/\partial\theta_i < 0$. Therefore, the equilibrium ECSR levels are obtained as

$$\theta_i^{\mathrm{II}} = 0,\ \theta_j^{\mathrm{II}} = 0. \tag{A.9}$$

Other equilibrium values of the full game are derived in Table A1(II).

(3) Scenario III: Noncooperative ECSR and ERJV competition

In this case, both firms form an ERJV and voluntarily and fully share their technological information on pollution abatement. This circumstance is described by $\delta = 1$.

In stage 3, manager i noncooperatively determines q_i to maximize $V_i(z_i,z_j)$. The analysis of stage 3 is identical to that in Subsection 3.1. In stage 2, manager i noncooperatively chooses the environmental R&D effort level z_i to maximize the objective function:

$$\begin{aligned} V_i(z_i,z_j) = \{&A-(q_i(\theta_i,\theta_j)+q_j(\theta_i,\theta_j))\}q_i(\theta_i,\theta_j)-t\{q_i(\theta_i,\theta_j)-z_i\} \\ &-\{(\gamma/2)z_i^2-z_i z_j\}-\theta_i d\{q_i(\theta_i,\theta_j)-z_i+q_j(\theta_i,\theta_j)-z_j\} \end{aligned} \tag{A.10}$$

From the corresponding first-order conditions for maximization $\partial V_i(z_i,z_j)/\partial z_i = 0 = \partial\, V_j(z_i,z_j)/\partial z_j$, the equilibrium R&D effort levels are obtained as

$$z_i(\theta_i,\theta_j) = \frac{d(\gamma\theta_i+\theta_j)+(1+\gamma)t}{(\gamma+1)(\gamma-1)}, \tag{A.11}$$

$$z_j(\theta_i,\theta_j) = \frac{d(\theta_i + \gamma\theta_j) + (1+\gamma)t}{(\gamma+1)(\gamma-1)}. \tag{A.12}$$

In stage 1, the owners of firm i noncooperatively determine θ_i to maximize its own profit: $\pi_i(\theta_i,\theta_j) = \{A - (q_i(\theta_i,\theta_j) + q_j(\theta_i,\theta_j))\}q_i(\theta_i,\theta_j) - t\{q_i(\theta_i,\theta_j) - z_i(\theta_i,\theta_j)\} - \{[z_i(\theta_i,\theta_j)]^2 - z_i(\theta_i,\theta_j)z_j(\theta_i,\theta_j)\}$. The corresponding first-order condition is derived as $\partial\pi_i/\partial\theta_i < 0.$ Therefore, the equilibrium ECSR levels are obtained as

$$\theta_i^{\mathrm{III}} = 0,\ \theta_j^{\mathrm{III}} = 0. \tag{A.13}$$

Table A1(III) summarizes all the equilibrium values of scenario III.

(4) Scenario V: Cooperative ECSR and noncooperative environmental R&D

In stage 3, manager i noncooperatively determines the output level q_i to maximize $V_i(z_i,z_j)$. The equilibrium output level derived at stage 3 is identical to that in Subsection 3.1. In stage 2, manager i noncooperatively chooses z_i to maximize $V_i(z_i,z_j)$:

$$\begin{aligned} V_i(z_i,z_j) = {} & \{A - (q_i(\theta_i,\theta_j) + q_j(\theta_i,\theta_j))\}q_i(\theta_i,\theta_j) - t\{q_i(\theta_i,\theta_j) - z_i\} \\ & -\{(\gamma/2)z_i^2 - \delta z_i z_j\} - \theta_i d\{q_i(\theta_i,\theta_j) - z_i + q_j(\theta_i,\theta_j) - z_j\}. \end{aligned} \tag{A.14}$$

From the corresponding first-order conditions for maximization $\partial V_i(z_i,z_j)/\partial z_i = 0 = \partial V_j(z_i,z_j)/\partial z_j$, the equilibrium R&D effort levels of two firms are derived as

$$z_i(\theta_i,\theta_j) = \frac{d(\theta_i\gamma + \theta_j\delta) + (\delta+\gamma)t}{(\gamma+\delta)(\gamma-\delta)}, \tag{A.15}$$

$$z_j(\theta_i,\theta_j) = \frac{d(\theta_i\delta + \theta_j\gamma) + (\delta+\gamma)t}{(\gamma+\delta)(\gamma-\delta)}. \tag{A.16}$$

In stage 1, the owners of firm i cooperatively determine the level of θ_i required to maximize the joint profits: $\pi_i(\theta_i,\theta_j) + \pi_j(\theta_i,\theta_j)$. From the corresponding first-order condition $\partial(\pi_i(\theta_i,\theta_j) + \pi_j(\theta_i,\theta_j))/\partial\theta_i = 0 = \partial\ (\pi_i(\theta_i,\theta_j) + \pi_j(\theta_i,\theta_j))/\partial\theta_j$, the equilibrium ECSR levels are obtained as

$$\theta_i^{\mathrm{V}} = \frac{(A-t)(\gamma-\delta)^2 + 9\delta t}{d(4\delta^2 + (\gamma-2\delta)(4\gamma+9))}, \tag{A.17}$$

$$\theta_j^{\mathrm{V}} = \frac{(A-t)(\gamma-\delta)^2 + 9\delta t}{d(4\delta^2 + (\gamma-2\delta)(4\gamma+9))}. \tag{A.18}$$

Other equilibrium values of scenario V are derived in Table A1(V).

(5) Scenario VI: Cooperative ECSR and cooperative environment R&D

In stage 3, manager i noncooperatively determines q_i to maximize $V_i(z_i,z_j)$. The equilibrium output level obtained at stage 3 is identical to that in Subsection 3.1. In stage 2, manager i cooperatively chooses its own abatement z_i to maximize the summation of two objective functions:

$$\begin{aligned} V_i(z_i,z_j) + V_j(z_i,z_j) = {} & \{A - (q_i(\theta_i,\theta_j) + q_j(\theta_i,\theta_j))\}q_i(\theta_i,\theta_j) - t\{q_i(\theta_i,\theta_j) - z_i\} \\ & -\{(\gamma/2)z_i^2 - \delta z_i z_j\} - \theta_i d\{q_i(\theta_i,\theta_j) - z_i + q_j(\theta_i,\theta_j) - z_j\} \\ & +\{A - (q_i(\theta_i,\theta_j) + q_j(\theta_i,\theta_j))\}q_j(\theta_i,\theta_j) - t\{q_j(\theta_i,\theta_j) - z_j\} \\ & -\{(\gamma/2)z_j^2 - \delta z_i z_j\} - \theta_j d\{q_i(\theta_i,\theta_j) - z_i + q_j(\theta_i,\theta_j) - z_j\}. \end{aligned} \tag{A.19}$$

From the corresponding first-order conditions for maximization $\partial(V_i(z_i,z_j)+V_j(z_i,z_j))/\partial z_i = 0 = \partial(V_i(z_i,z_j)+V_j(z_i,z_j))/\partial z_j$, the equilibrium R&D effort levels of two firms are derived as

$$z_i(\theta_i,\theta_j) = \frac{d(\theta_i+\theta_j)+t}{\gamma-2\delta}, \tag{A.20}$$

$$z_j(\theta_i,\theta_j) = \frac{d(\theta_i+\theta_j)+t}{\gamma-2\delta}. \tag{A.21}$$

In stage 1, the owners of firm i cooperatively determine θ_i to maximize the joint profits: $\pi_i(\theta_i,\theta_j)+\pi_j(\theta_i,\theta_j)$. From the corresponding first-order condition $\partial(\pi_i(\theta_i,\theta_j)+\pi_j(\theta_i,\theta_j))/\partial\theta_i = 0 = \partial\ (\pi_i(\theta_i,\theta_j)+\pi_j(\theta_i,\theta_j))/\partial\theta_j$, the equilibrium ECSR levels are obtained as

$$\theta_i^{\mathrm{VI}} = \frac{(A-t)(\gamma-2\delta)}{4d(\gamma-2\delta+9)}, \tag{A.22}$$

$$\theta_j^{\mathrm{VI}} = \frac{(A-t)(\gamma-2\delta)}{4d(\gamma-2\delta+9)}. \tag{A.23}$$

Other equilibrium values are listed in Table A1(VI).

Appendix B:

Table A1(I): Equilibrium outcome under Scenario I

	Noncooperative ECSR and noncooperative environmental R&D
ECSR level	$\theta^{\mathrm{I}} = 0$
Environmental R&D effort	$z^{\mathrm{I}} = \frac{t}{\gamma-\delta}$
Output	$q^{\mathrm{I}} = \frac{A-t}{3}$
Pollution emission	$e^{\mathrm{I}} = \frac{A(\gamma-\delta)-(\gamma-\delta+3)t}{3(\gamma-\delta)}$
Profit	$\pi^{\mathrm{I}} = (q^{\mathrm{I}})^2 + tz^{\mathrm{I}} - (\gamma/2)(z^{\mathrm{I}})^2 + \delta(z^{\mathrm{I}})^2$
Social welfare	$W^{\mathrm{I}} = 2(q^{\mathrm{I}})^2 + 2\pi^{\mathrm{I}} + 2te^{\mathrm{I}} - 2de^{\mathrm{I}}$

Table A1(II): Equilibrium outcomes under Scenario II

	Noncooperative ECSR and cooperative environmental R&D
ECSR level	$\theta^{\mathrm{II}} = 0$
Environmental R&D effort	$z^{\mathrm{II}} = \frac{t}{\gamma-\delta}$
Output	$q^{\mathrm{II}} = \frac{A-t}{3}$
Pollution emission	$e^{\mathrm{II}} = \frac{A(\gamma-\delta)-(\gamma-\delta+3)t}{3(\gamma-\delta)}$
Profit	$\pi^{\mathrm{II}} = (q^{\mathrm{II}})^2 + tz^{\mathrm{II}} - (\gamma/2)(z^{\mathrm{II}})^2 + \delta(z^{\mathrm{II}})^2$
Social welfare	$W^{\mathrm{II}} = 2(q^{\mathrm{II}})^2 + 2\pi^{\mathrm{II}} + 2te^{\mathrm{II}} - 2de^{\mathrm{II}}$

Table A1(III): Equilibrium outcomes under Scenario III

	Noncooperative ECSR and ERJV competition
ECSR level	$\theta^{\mathrm{III}} = 0$
Environmental R&D effort	$z^{\mathrm{III}} = \dfrac{t}{\gamma - 1}$
Output	$q^{\mathrm{III}} = \dfrac{A - t}{3}$
Pollution emission	$e^{\mathrm{III}} = \dfrac{(\gamma - 1)A - (\gamma + 2)t}{3(\gamma - 1)}$
Profit	$\pi^{\mathrm{III}} = (q^{\mathrm{III}})^2 + tz^{\mathrm{III}} - (\gamma/2)(z^{\mathrm{III}})^2 + (z^{\mathrm{III}})^2$
Social welfare	$W^{\mathrm{III}} = 2(q^{\mathrm{III}})^2 + 2\pi^{\mathrm{III}} + 2te^{\mathrm{III}} - 2de^{\mathrm{III}}$

Table A1(IV): Equilibrium outcome under Scenario IV

	Noncooperative ECSR and ERJV cooperation
ECSR level	$\theta^{\mathrm{IV}} = 0$
Environmental R&D effort	$z^{\mathrm{IV}} = \dfrac{t}{\gamma - 2}$
Output	$q^{\mathrm{IV}} = \dfrac{A - t}{3}$
Pollution emission	$e^{\mathrm{IV}} = \dfrac{(\gamma - 2)A - (\gamma + 1)t}{3(\gamma - 2)}$
Profit	$\pi^{\mathrm{IV}} = (q^{\mathrm{IV}})^2 + tz^{\mathrm{IV}} - (\gamma/2)(z^{\mathrm{IV}})^2 + (z^{\mathrm{IV}})^2$
Social welfare	$W^{\mathrm{IV}} = 2(q^{\mathrm{IV}})^2 + 2\pi^{\mathrm{IV}} + 2te^{\mathrm{IV}} - 2de^{\mathrm{IV}}$

Table A1(V): Equilibrium outcome under Scenario V

	Cooperative ECSR and noncooperative environmental R&D
ECSR level	$\theta^{\mathrm{V}} = \dfrac{(A - t)(\gamma - \delta)^2 + 9\delta t}{d(4\delta^2 + (\gamma - 2\delta)(9 + 4\gamma))}$
Environmental R&D effort	$z^{\mathrm{V}} = \dfrac{A(\gamma - \delta) + 3(3 + \gamma - \delta)t}{4\delta^2 + (\gamma - 2\delta)(9 + 4\gamma)}$
Output	$q^{\mathrm{V}} = \dfrac{A(\delta^2 + (\gamma - 2\delta)(3 + \gamma)) - (\delta^2 + \gamma(3 + \gamma) - \delta(3 + 2\gamma))t}{4\delta^2 + (\gamma - 2\delta)(9 + 4\gamma)}$
Pollution emission	$e^{\mathrm{V}} = \dfrac{A(\delta^2 + \gamma(2 + \gamma) - \delta(5 + 2\gamma)) - (3 + \gamma - \delta)^2 t}{4\delta^2 + (\gamma - 2\delta)(9 + 4\gamma)}$
Profit	$\pi^{\mathrm{V}} = (q^{\mathrm{V}})^2 + tz^{\mathrm{V}} - (\gamma/2)(z^{\mathrm{V}})^2 + \delta(z^{\mathrm{V}})^2$
Social welfare	$W^{\mathrm{V}} = 2(q^{\mathrm{V}})^2 + 2\pi^{\mathrm{V}} + 2te^{\mathrm{V}} - 2de^{\mathrm{V}}$

Table A1(VI): Equilibrium outcome under Scenario VI

	Cooperative ECSR and cooperative environmental R&D
ECSR level	$\theta^{\mathrm{VI}} = \frac{(\gamma - 2\delta)(A - t)}{4d(\gamma - 2\delta + 9)}$
Environmental R&D effort	$z^{\mathrm{VI}} = \frac{(A - t)(\gamma - 2\delta) + 2(\gamma - 2\delta + 9)t}{2(\gamma - 2\delta + 9)(\gamma - 2\delta)}$
Output	$q^{\mathrm{VI}} = \frac{(\gamma - 2\delta + 12)(A - t)}{4(9 + \gamma) - 8\delta}$
Pollution emission	$e^{\mathrm{VI}} = \frac{A(10 + \gamma - 2\delta)(\gamma - 2\delta) - ((\gamma - 2\delta)(14 + \gamma - 2\delta) + 36)t}{4(9 + \gamma - 2\delta)(\gamma - 2\delta)}$
Profit	$\pi^{\mathrm{VI}} = (q^{\mathrm{VI}})^2 + tz^{\mathrm{VI}} - (\gamma/2)(z^{\mathrm{VI}})^2 + \delta(z^{\mathrm{VI}})^2$
Social welfare	$W^{\mathrm{VI}} = 2(q^{\mathrm{VI}})^2 + 2\pi^{\mathrm{VI}} + 2te^{\mathrm{VI}} - 2de^{\mathrm{VI}}$

Table A1(VII): Equilibrium outcomes under Scenario VII

	Cooperative ECSR and ERJV competition
ECSR level	$\theta^{\mathrm{VII}} = \frac{(A - t)(\gamma - 1)^2 + 9t}{d(4 + (\gamma - 2)(9 + 4\gamma))}$
Environmental R&D effort	$z^{\mathrm{VII}} = \frac{A(\gamma - 1) + 3(2 + \gamma)t}{4 + (\gamma - 2)(9 + 4\gamma)}$
Output	$q^{\mathrm{VII}} = \frac{A(\gamma^2 + \gamma - 5) - (\gamma^2 + \gamma - 2)t}{4 + (\gamma - 2)(9 + 4\gamma)}$
Pollution emission	$e^{\mathrm{VII}} = \frac{(\gamma + 2)[A(\gamma - 2) - (\gamma + 2)t]}{4 + (\gamma - 2)(9 + 4\gamma)}$
Profit	$\pi^{\mathrm{VII}} = (q^{\mathrm{VII}})^2 + tz^{\mathrm{VII}} - (\gamma/2)(z^{\mathrm{VII}})^2 + (z^{\mathrm{VII}})^2$
Social welfare	$W^{\mathrm{VII}} = 2(q^{\mathrm{VII}})^2 + 2\pi^{\mathrm{VII}} + 2te^{\mathrm{VII}} - 2de^{\mathrm{VII}}$

Table A1(VIII): Equilibrium outcome under Scenario VIII

	Cooperative ECSR and ERJV cooperation
ECSR level	$\theta^{\mathrm{VIII}} = \frac{(\gamma - 2)(A - t)}{4d(\gamma + 7)}$
Environmental R&D effort	$z^{\mathrm{VIII}} = \frac{A(\gamma - 2) + (\gamma + 16)t}{2(\gamma + 7)(\gamma - 2)}$
Output	$q^{\mathrm{VIII}} = \frac{(\gamma + 10)(A - t)}{4(\gamma + 7)}$
Pollution emission	$e^{\mathrm{VIII}} = \frac{(\gamma + 8)(\gamma - 2)A - (\gamma^2 + 10\gamma + 12)t}{4(\gamma + 7)(\gamma - 2)}$
Profit	$\pi^{\mathrm{VIII}} = (q^{\mathrm{VIII}})^2 + tz^{\mathrm{VIII}} - (\gamma/2)(z^{\mathrm{VIII}})^2 + (z^{\mathrm{VIII}})^2$
Social welfare	$W^{\mathrm{VIII}} = 2(q^{\mathrm{VIII}})^2 + 2\pi^{\mathrm{VIII}} + 2te^{\mathrm{VIII}} - 2de^{\mathrm{VIII}}$

Appendix C:

Proof of Proposition 1:

From Table A1(I-VIII), we readily obtain

$$\theta^{\mathrm{VI}} - \theta^{\mathrm{VIII}} = \frac{9(1-\delta)(A-t)}{2d(7+\gamma)(9-2\delta+\gamma)} \geq 0, \tag{C.1}$$

$$\theta^{\mathrm{V}} - \theta^{\mathrm{VII}} = \frac{-9(1-\delta)(A(\delta(r-2)+\gamma)+(4-\delta)(2+\gamma)t)}{d(4\gamma^2+\gamma-14)(9(\gamma-2\delta)+4(\gamma-\delta)^2)} \leq 0. \tag{C.2}$$

When $\delta = 1$, then $\theta^{\mathrm{VI}} = \theta^{\mathrm{VIII}}$ and $\theta^{\mathrm{V}} = \theta^{\mathrm{VII}}$.

Furthermore, we straightforwardly have

$$\begin{aligned}\theta^{\mathrm{V}} - \theta^{\mathrm{VI}} &= \frac{9\big(A(3\gamma-4\delta)\gamma+\big(-8\delta^2-3\gamma^2+4\delta(9+2\gamma)\big)t\big)}{4d(9-2\delta+\gamma)\big(4\delta^2+(\gamma-2\delta)(9+4\gamma)\big)} \\ &> \frac{9\delta t}{d\big(4\delta^2+(\gamma-2\delta)(9+4\gamma)\big)} \geq 0,\end{aligned} \tag{C.3}$$

by using $A > t$, which is derived by the assumption of $A > 5t$.

Therefore, we obtain $\theta^{\mathrm{VII}} \geq \theta^{\mathrm{V}} > \theta^{\mathrm{VI}} \geq \theta^{\mathrm{VIII}} > \theta^{\mathrm{I}} = \theta^{\mathrm{II}} = \theta^{\mathrm{III}} = \theta^{\mathrm{IV}} = 0$. ■

Appendix D:

Proof of Proposition 2:

Under the assumption of $A > 5t$, we straightforwardly obtain the following results:

$$z^{\mathrm{VII}} - z^{\mathrm{I}} = \frac{2A(3-\delta)+5(4-3\delta)t}{25(3-\delta)} > 0, \tag{D.1}$$

$$z^{\mathrm{VIII}} - z^{\mathrm{I}} = \frac{A-t}{20} + \left(\frac{2-\delta}{3-\delta}\right)t > 0, \tag{D.2}$$

$$z^{\mathrm{VII}} - z^{\mathrm{II}} = \frac{4(A+5t)(1-\delta)+2(A-5\delta t)}{53(3-2\delta)} > 0, \tag{D.3}$$

$$z^{\mathrm{VIII}} - z^{\mathrm{II}} = \frac{(2A+t)(1-\delta)+A-\delta t}{20(3-2\delta)} > 0, \tag{D.4}$$

$$z^{\mathrm{VII}} - z^{\mathrm{III}} = \frac{4A+5t}{50} > 0, \tag{D.5}$$

$$z^{\mathrm{VIII}} - z^{\mathrm{III}} = \frac{A+9t}{20} > 0, \tag{D.6}$$

$$z^{\mathrm{VII}} - z^{\mathrm{IV}} = \frac{2(A-5t)}{25} > 0, \tag{D.7}$$

$$z^{\mathrm{VIII}} - z^{\mathrm{IV}} = \frac{A-t}{20} > 0, \tag{D.8}$$

$$z^{\mathrm{VII}} - z^{\mathrm{V}} = \frac{(1-\delta)(A(51-8\delta)+15(33-4\delta)t)}{25(63-42\delta+4\delta^2)} \geq 0, \tag{D.9}$$

$$z^{\mathrm{VIII}} - z^{\mathrm{V}} = \frac{A(3-22\delta+4\delta^2)+(837-738\delta+76\delta^2)t}{20(63-42\delta+4\delta^2)}, \tag{D.10}$$

$$z^{\mathrm{VII}} - z^{\mathrm{VI}} = \frac{A(69-70\delta+16\delta^2)+5(111-170\delta+24\delta^2)t}{100(6-\delta)(3-2\delta)}, \tag{D.11}$$

$$z^{\mathrm{VIII}} - z^{\mathrm{VI}} = \frac{(1-\delta)(A(3-2\delta) + (237-38\delta)t)}{20(3-2\delta)(6-\delta)} \geq 0, \tag{D.12}$$

$$z^{\mathrm{VII}} - z^{\mathrm{VIII}} = \frac{3A-35t}{100}. \tag{D.13}$$

When $0 \leq \delta < 1$, then $z^{\mathrm{VII}} > z^{\mathrm{V}}$ and$z^{\mathrm{VIII}} > z^{\mathrm{VI}}$. Furthermore, when $\delta = 1$, then $z^{\mathrm{VII}} = z^{\mathrm{V}}$ and $z^{\mathrm{VIII}} = z^{\mathrm{VI}}$. However, each sign of $z^{\mathrm{VIII}} - z^{\mathrm{V}}$, $z^{\mathrm{VII}} - z^{\mathrm{VI}}$, and $z^{\mathrm{VII}} - z^{\mathrm{VIII}}$ is indeterminate.

Here, noting the numerators of the right-hand side of equations (D.10-11), we define the following:

$$G_1(\delta) \equiv \frac{-3+22\delta-4\delta^2}{837-738\delta+76\delta^2}, \tag{D.14}$$

$$G_2(\delta) \equiv \frac{-69+70\delta-16\delta^2}{5(111-170\delta+24\delta^2)}. \tag{D.15}$$

Then, $G_1'(\delta) > 0$ for all $\delta \in [0,1]$. Thus, if $t/A > (<) G_1(1) = 3/35$ (*i.e.*, $t > (<)(3/35)A$), then $z^{\mathrm{VIII}} > (<) z^{\mathrm{V}}$. Furthermore, $G_2(\delta) > 0$ for all $\delta \in [0, (85-\sqrt{4561})/24]$ and $G_2'(\delta) < 0$ for all $\delta \in ((85-\sqrt{4561})/24, 1]$. Thus, if $t/A < (>) G_2(1) = 3/35$ (*i.e.*, $t < (>)(3/35)A$), then $z^{\mathrm{VII}} > (<) z^{\mathrm{VI}}$. Finally, from (D.13), if $t < (>)(3/35)A$, then $z^{\mathrm{VII}} > (<) z^{\mathrm{VIII}}$.

Therefore, when $0 < t < (3/35)A$, the environmental R&D effort level under scenario VII is greater than that under the other seven scenarios; when $(3/35)A < t < (1/5)A$, the environmental R&D effort level under scenario VIII is greater than that under the other seven scenarios. ■

Appendix E:

The comparison results for two different equilibrium values of $z^{\mathrm{h}}(\mathrm{h} = \mathrm{I}, \mathrm{II}, \mathrm{III}, \mathrm{IV}, \mathrm{V}, \mathrm{VI}, \mathrm{VII}, \mathrm{VIII})$, whose sign is determined, have already been partially derived in (D.1)-(D.9) and (D.12). Other comparative results for which the sign has been determined are as follows.

$$z^{\mathrm{II}} - z^{\mathrm{I}} = \frac{\delta t}{(3-\delta)(3-2\delta)} \geq 0, \tag{E.1}$$

$$z^{\mathrm{III}} - z^{\mathrm{I}} = \frac{(1-\delta)t}{2(3-\delta)} \geq 0, \tag{E.2}$$

$$z^{\mathrm{IV}} - z^{\mathrm{I}} = \frac{(2-\delta)t}{(3-\delta)} > 0, \tag{E.3}$$

$$z^{\mathrm{V}} - z^{\mathrm{I}} = \frac{(A-t)(3-\delta)^2 + 9\delta t}{(3-\delta)\left(4(3-\delta)^2 + 9(3-2\delta)\right)} > 0, \tag{E.4}$$

$$z^{\mathrm{VI}} - z^{\mathrm{I}} = \frac{A-t}{4(6-\delta)} + \frac{\delta t}{2\delta^2 - 9\delta + 9} > 0, \tag{E.5}$$

$$z^{\mathrm{IV}} - z^{\mathrm{II}} = \frac{2(1-\delta)t}{3-2\delta} \geq 0, \tag{E.6}$$

$$z^{\mathrm{V}} - z^{\mathrm{II}} = \frac{(3-\delta)(2A(1-\delta) + A - (3+2\delta)t)}{(3-2\delta)\left(4(3-\delta)^2 + 9(3-2\delta)\right)} > 0, \tag{E.7}$$

$$z^{\mathrm{VI}} - z^{\mathrm{II}} = \frac{A-t}{4(6-\delta)} > 0, \tag{E.8}$$

$$z^{\mathrm{IV}} - z^{\mathrm{III}} = \frac{t}{2} > 0, \tag{E.9}$$

$$z^{\mathrm{V}} - z^{\mathrm{III}} = \frac{(3-\delta)(2A-(9-4\delta)t)+15\delta t}{2\big(4\delta^2+21(3-2\delta)\big)} > 0, \tag{E.10}$$

$$z^{\mathrm{VI}} - z^{\mathrm{III}} = \frac{(3-2\delta)(A-(5-2\delta)t)+12\delta t}{4(6-\delta)(3-2\delta)} > 0, \tag{E.11}$$

$$z^{\mathrm{VII}} - z^{\mathrm{III}} = \frac{4A+5t}{50} > 0, \tag{E.12}$$

$$z^{\mathrm{VIII}} - z^{\mathrm{III}} = \frac{A+9t}{20} > 0, \tag{E.13}$$

$$z^{\mathrm{VII}} - z^{\mathrm{IV}} = \frac{2(A-5t)}{25} > 0, \tag{E.14}$$

$$z^{\mathrm{VIII}} - z^{\mathrm{IV}} = \frac{A-t}{20} > 0, \tag{E.15}$$

$$z^{\mathrm{VII}} - z^{\mathrm{V}} = \frac{(1-\delta)(A(51-8\delta)+15(33-4\delta)t)}{25(63-42\delta+4\delta^2)} \geq 0. \tag{E.16}$$

Here, when $\delta = 0$, then $z^{\mathrm{II}} = z^{\mathrm{I}}$. Furthermore, when $\delta = 1$, then $z^{\mathrm{III}} = z^{\mathrm{I}}$, $z^{\mathrm{IV}} = z^{\mathrm{II}}$ and $z^{\mathrm{VII}} = z^{\mathrm{V}}$.

The comparative results for which the sign is indeterminate are as follows.

$$z^{\mathrm{III}} - z^{\mathrm{II}} = \frac{(1-2\delta)t}{2(3-2\delta)}. \tag{E.17}$$

When $0 < \delta < 1/2$ ($\delta = 1/2$), then $z^{\mathrm{III}} > z^{\mathrm{II}}$($z^{\mathrm{III}} = z^{\mathrm{II}}$). However, when $1/2 < \delta < 1$, then $z^{\mathrm{III}} < z^{\mathrm{II}}$.

$$z^{\mathrm{V}} - z^{\mathrm{IV}} = \frac{A(3-\delta)-(4\delta^2-39\delta+45)t}{(4\delta^2-42\delta+63)}. \tag{E.18}$$

Here, because $\left(\frac{3-\delta}{4\delta^2-39\delta+45}\right) \leq \frac{1}{5}$, when $0 < t < (1/15)A$, then $z^{\mathrm{V}} > z^{\mathrm{IV}}$ for all $\delta \in [0,1]$; when $t = (1/15)A$, then $z^{\mathrm{V}} = z^{\mathrm{IV}}$. However, when $(1/15)A < t < (1/5)A$, then (i) $z^{\mathrm{V}} < z^{\mathrm{IV}}$ for all $\delta \in [0, \bar{\delta}_z^{45}(m))$, where $\bar{\delta}_z^{45}(m) \equiv \{\delta | A(3-\delta)-(4\delta^2-39\delta+45)t = 0, \delta \in [0,1], t/A < 1/5\}$; (ii) $z^{\mathrm{V}} = z^{\mathrm{IV}}$ for $\delta = \bar{\delta}_z^{45}(m)$; and (iii) $z^{\mathrm{V}} > z^{\mathrm{IV}}$ for all $\delta \in (\bar{\delta}_z^{45}(m),1]$.

$$z^{\mathrm{VI}} - z^{\mathrm{IV}} = \frac{A(3-2\delta)-(8\delta^2-58\delta+51)t}{4(3-2\delta)(6-\delta)}. \tag{E.19}$$

When $0 < t < (3/51)A$, then $z^{\mathrm{VI}} > z^{\mathrm{IV}}$ for all $\delta \in [0,1]$; when $t = (3/51)A$, then $z^{\mathrm{VI}} = z^{\mathrm{IV}}$. However, when $(3/51)A < t < (1/5)A$, then (i) $z^{\mathrm{VI}} < z^{\mathrm{IV}}$ for all $\delta \in [0, \bar{\delta}_z^{46}(m))$, where $\bar{\delta}_z^{46}(m) \equiv \{\delta | A(3-2\delta)-(8\delta^2-58\delta+51)t = 0, \delta \in [0,1], m \equiv t/A < 1/5\}$; (ii) $z^{\mathrm{V}} = z^{\mathrm{IV}}$ for $\delta = \bar{\delta}_z^{46}(m)$; and (iii) $z^{\mathrm{VI}} > z^{\mathrm{IV}}$ for all $\delta \in (\bar{\delta}_z^{46}(m),1]$.

$$z^{\mathrm{V}} - z^{\mathrm{VI}} = \frac{3A(3+2\delta)(3-2\delta)-(27+288\delta-156\delta^2+16\delta^3)t}{4(6-\delta)(3-2\delta)(63-42\delta+4\delta^2)}. \tag{E.20}$$

When $0 < t < (3/35)A$, then $z^{\mathrm{V}} > z^{\mathrm{VI}}$ for all $\delta \in [0,1]$; when $t = (3/35)A$, then $z^{\mathrm{V}} = z^{\mathrm{VI}}$. However, when $(3/35)A < t < (1/5)A$, then (i) $z^{\mathrm{V}} > z^{\mathrm{VI}}$ for all $\delta \in [0, \bar{\delta}_z^{56}(m))$, where $\bar{\delta}_z^{56}(m) \equiv \{\delta | 3A(3+2\delta)(3-2\delta)-(27+288\delta-156\delta^2+16\delta^3)t = 0, \delta \in [0,1], m \equiv t/A < 1/5\}$; (ii) $z^{\mathrm{V}} = z^{\mathrm{VI}}$ for $\delta = \bar{\delta}_z^{56}(m)$; and (iii) $z^{\mathrm{V}} < z^{\mathrm{VI}}$ for all $\delta \in (\bar{\delta}_z^{56}(m),1]$.

$$z^{\mathrm{VIII}} - z^{\mathrm{V}} = \frac{A(3-22\delta+4\delta^2)+(837-738\delta+76\delta^2)t}{20(63-42\delta+4\delta^2)}. \tag{E.21}$$

When $0 < t < (3/35)A$, then (i) $z^{\mathrm{V}} < z^{\mathrm{VIII}}$ for all $\delta \in [0, \bar{\delta}_z^{58}(m))$, where $\bar{\delta}_z^{58}(m) \equiv \{\delta | A(3-22\delta+4\delta^2)+(837-738\delta+76\delta^2)t = 0, \delta \in [0,1], m \equiv t/A < 1/5\}$; (ii) $z^{\mathrm{V}} = z^{\mathrm{VIII}}$ for $\delta = \bar{\delta}_z^{58}(m)$; and (iii) $z^{\mathrm{V}} > z^{\mathrm{VIII}}$

for all $\delta \in (\bar{\delta}_z^{58}(m),1]$. However, when $t = (3/35)A$, then $z^{\mathrm{V}} = z^{\mathrm{VIII}}$; when $(3/35)A < t < (1/5)A$, then $z^{\mathrm{V}} < z^{\mathrm{VIII}}$ for all$\delta \in [0,1]$.

$$z^{\mathrm{VII}} - z^{\mathrm{VI}} = \frac{A(69 - 70\delta + 16\delta^2) + 5(111 - 170\delta + 24\delta^2)t}{100(6-\delta)(3-2\delta)}. \tag{E.22}$$

When $0 < t < (3/35)A$, then $z^{\mathrm{VII}} > z^{\mathrm{VI}}$ for all $\delta \in [0,1]$; when $t = (3/35)A$, then $z^{\mathrm{VII}} = z^{\mathrm{VI}}$. However, when $(3/35)A < t < (1/5)A$, then (i) $z^{\mathrm{VII}} > z^{\mathrm{VI}}$ for all $\delta \in [0, \bar{\delta}_z^{67}(m))$, where $\bar{\delta}_z^{67}(m) \equiv \{\delta | A(69 - 70\delta + 16\delta^2) + 5(111 - 170\delta + 24\delta^2)t = 0, \delta \in [0,1], m \equiv t/A < 1/5\}$; (ii) $z^{\mathrm{VII}} = z^{\mathrm{VI}}$ for $\delta = \bar{\delta}_z^{67}(m)$; and (iii) $z^{\mathrm{VII}} < z^{\mathrm{VI}}$ for all $\delta \in (\bar{\delta}_z^{67}(m),1]$.

$$z^{\mathrm{VII}} - z^{\mathrm{VIII}} = \frac{3A - 35t}{100}. \tag{E.23}$$

When $0 < t < (3/35)A$, then $z^{\mathrm{VII}} > z^{\mathrm{VIII}}$ for all $\delta \in [0,1]$; when $t = (3/35)A$, then $z^{\mathrm{VII}} = z^{\mathrm{VIII}}$. However, when $(3/35)A < t < (1/5)A$, $z^{\mathrm{VII}} < z^{\mathrm{VIII}}$ for all $\delta \in [0,1]$.

Based on the results above, we obtain the ranking of the abatement levels under eight scenarios after some manipulation as follows:

(1) When $0 < t < (7/487)A$, then
[i] $z^{\mathrm{VII}} > z^{\mathrm{VIII}} > z^{\mathrm{V}} > z^{\mathrm{VI}} > z^{\mathrm{IV}} > z^{\mathrm{III}} > z^{\mathrm{II}} > z^{\mathrm{I}}$ for all $0 \le \delta < \bar{\delta}_z^{58}(m)$.
[ii] $z^{\mathrm{VII}} > z^{\mathrm{VIII}} = z^{\mathrm{V}} > z^{\mathrm{VI}} > z^{\mathrm{IV}} > z^{\mathrm{III}} > z^{\mathrm{II}} > z^{\mathrm{I}}$ for $\delta = \bar{\delta}_z^{58}(m)$.
[iii] $z^{\mathrm{VII}} > z^{\mathrm{V}} > z^{\mathrm{VIII}} > z^{\mathrm{VI}} > z^{\mathrm{IV}} > z^{\mathrm{III}} > z^{\mathrm{II}} > z^{\mathrm{I}}$ for all $\bar{\delta}_z^{58}(m) < \delta < 1/2$.
[iv] $z^{\mathrm{VII}} > z^{\mathrm{V}} > z^{\mathrm{VIII}} > z^{\mathrm{VI}} > z^{\mathrm{IV}} > z^{\mathrm{III}} = z^{\mathrm{II}} > z^{\mathrm{I}}$ for $\delta = 1/2$.
[v] $z^{\mathrm{VII}} > z^{\mathrm{V}} > z^{\mathrm{VIII}} > z^{\mathrm{VI}} > z^{\mathrm{IV}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $1/2 < \delta < 1$.
[vi] $z^{\mathrm{VII}} > z^{\mathrm{V}} > z^{\mathrm{VIII}} > z^{\mathrm{VI}} > z^{\mathrm{IV}} = z^{\mathrm{II}} > z^{\mathrm{III}} = z^{\mathrm{I}}$ for $\delta = 1$.

(2) When $t = (7/487)A$, then
[i] $z^{\mathrm{VII}} > z^{\mathrm{VIII}} > z^{\mathrm{V}} > z^{\mathrm{VI}} > z^{\mathrm{IV}} > z^{\mathrm{III}} > z^{\mathrm{II}} > z^{\mathrm{I}}$ for all $0 \le \delta < \bar{\delta}_z^{58}(m)$.
[ii] $z^{\mathrm{VII}} > z^{\mathrm{VIII}} = z^{\mathrm{V}} > z^{\mathrm{VI}} > z^{\mathrm{IV}} > z^{\mathrm{III}} = z^{\mathrm{II}} > z^{\mathrm{I}}$ for $\delta = \bar{\delta}_z^{58}(m = 7/487)(= 1/2)$.
[iii] $z^{\mathrm{VII}} > z^{\mathrm{V}} > z^{\mathrm{VIII}} > z^{\mathrm{VI}} > z^{\mathrm{IV}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $1/2 < \delta < 1$.
[iv] $z^{\mathrm{VII}} > z^{\mathrm{V}} > z^{\mathrm{VIII}} > z^{\mathrm{VI}} > z^{\mathrm{IV}} = z^{\mathrm{II}} > z^{\mathrm{III}} = z^{\mathrm{I}}$ for $\delta = 1$.

(3) When $(7/487)A < t \le (3/51)A$, then
[i] $z^{\mathrm{VII}} > z^{\mathrm{VIII}} > z^{\mathrm{V}} > z^{\mathrm{VI}} > z^{\mathrm{IV}} > z^{\mathrm{III}} > z^{\mathrm{II}} > z^{\mathrm{I}}$ for all $0 \le \delta < 1/2$.
[ii] $z^{\mathrm{VII}} > z^{\mathrm{VIII}} > z^{\mathrm{V}} > z^{\mathrm{VI}} > z^{\mathrm{IV}} > z^{\mathrm{III}} = z^{\mathrm{II}} > z^{\mathrm{I}}$ for $\delta = 1/2$.
[iii] $z^{\mathrm{VII}} > z^{\mathrm{VIII}} > z^{\mathrm{V}} > z^{\mathrm{VI}} > z^{\mathrm{IV}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $1/2 < \delta < \bar{\delta}_z^{58}(m)$.
[iv] $z^{\mathrm{VII}} > z^{\mathrm{VIII}} = z^{\mathrm{V}} > z^{\mathrm{VI}} > z^{\mathrm{IV}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for $\delta = \bar{\delta}_z^{58}(m)$.
[v] $z^{\mathrm{VII}} > z^{\mathrm{V}} > z^{\mathrm{VIII}} > z^{\mathrm{VI}} > z^{\mathrm{IV}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $\bar{\delta}_z^{58}(m) < \delta < 1$.
[vi] $z^{\mathrm{VII}} > z^{\mathrm{V}} > z^{\mathrm{VIII}} > z^{\mathrm{VI}} > z^{\mathrm{IV}} = z^{\mathrm{II}} > z^{\mathrm{III}} = z^{\mathrm{I}}$ for $\delta = 1$.

(4) When $(3/51)A < t \le (1/15)A$, then
[i] $z^{\mathrm{VII}} > z^{\mathrm{VIII}} > z^{\mathrm{V}} > z^{\mathrm{IV}} > z^{\mathrm{VI}} > z^{\mathrm{III}} > z^{\mathrm{II}} > z^{\mathrm{I}}$ for all $0 \le \delta < \bar{\delta}_z^{46}(m)$.
[ii]$z^{\mathrm{VII}} > z^{\mathrm{VIII}} > z^{\mathrm{V}} > z^{\mathrm{IV}} = z^{\mathrm{VI}} > z^{\mathrm{III}} > z^{\mathrm{II}} > z^{\mathrm{I}}$ for $\delta = \bar{\delta}_z^{46}(m)$.
[iii] $z^{\mathrm{VII}} > z^{\mathrm{VIII}} > z^{\mathrm{V}} > z^{\mathrm{VI}} > z^{\mathrm{IV}} > z^{\mathrm{III}} > z^{\mathrm{II}} > z^{\mathrm{I}}$ for all $\bar{\delta}_z^{46}(m) < \delta < 1/2$.
[iv] $z^{\mathrm{VII}} > z^{\mathrm{VIII}} > z^{\mathrm{V}} > z^{\mathrm{VI}} > z^{\mathrm{IV}} > z^{\mathrm{III}} = z^{\mathrm{II}} > z^{\mathrm{I}}$ for $\delta = 1/2$.

[v] $z^{\mathrm{VII}} > z^{\mathrm{VIII}} > z^{\mathrm{V}} > z^{\mathrm{VI}} > z^{\mathrm{IV}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $1/2 < \delta < \bar{\delta}_z^{58}(m)$.
[vi] $z^{\mathrm{VII}} > z^{\mathrm{VIII}} = z^{\mathrm{V}} > z^{\mathrm{VI}} > z^{\mathrm{IV}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for $\delta = \bar{\delta}_z^{58}(m)$.
[vii] $z^{\mathrm{VII}} > z^{\mathrm{V}} > z^{\mathrm{VIII}} > z^{\mathrm{VI}} > z^{\mathrm{IV}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $\bar{\delta}_z^{58}(m) < \delta < 1$.
[viii] $z^{\mathrm{VII}} > z^{\mathrm{V}} > z^{\mathrm{VIII}} > z^{\mathrm{VI}} > z^{\mathrm{IV}} = z^{\mathrm{II}} > z^{\mathrm{III}} = z^{\mathrm{I}}$ for $\delta = 1$.

(5) When $(1/15)A < t < (1/12)A$, then
[i]$z^{\mathrm{VII}} > z^{\mathrm{VIII}} > z^{\mathrm{IV}} > z^{\mathrm{V}} > z^{\mathrm{VI}} > z^{\mathrm{III}} > z^{\mathrm{II}} > z^{\mathrm{I}}$ for all $0 \leq \delta < \bar{\delta}_z^{45}(m)$.
[ii] $z^{\mathrm{VII}} > z^{\mathrm{VIII}} > z^{\mathrm{V}} = z^{\mathrm{IV}} > z^{\mathrm{VI}} > z^{\mathrm{III}} > z^{\mathrm{II}} > z^{\mathrm{I}}$ for $\delta = \bar{\delta}_z^{45}(m)$.
[iii] $z^{\mathrm{VII}} > z^{\mathrm{VIII}} > z^{\mathrm{V}} > z^{\mathrm{IV}} > z^{\mathrm{VI}} > z^{\mathrm{III}} > z^{\mathrm{II}} > z^{\mathrm{I}}$ for all $\bar{\delta}_z^{45}(m) < \delta < \bar{\delta}_z^{46}(m)$.
[iv] $z^{\mathrm{VII}} > z^{\mathrm{VIII}} > z^{\mathrm{V}} > z^{\mathrm{IV}} = z^{\mathrm{VI}} > z^{\mathrm{III}} > z^{\mathrm{II}} > z^{\mathrm{I}}$ for $\delta = \bar{\delta}_z^{46}(m)$.
[v] $z^{\mathrm{VII}} > z^{\mathrm{VIII}} > z^{\mathrm{V}} > z^{\mathrm{VI}} > z^{\mathrm{IV}} > z^{\mathrm{III}} > z^{\mathrm{II}} > z^{\mathrm{I}}$ for all $\bar{\delta}_z^{46}(m) < \delta < 1/2$.
[vi] $z^{\mathrm{VII}} > z^{\mathrm{VIII}} > z^{\mathrm{V}} > z^{\mathrm{VI}} > z^{\mathrm{IV}} > z^{\mathrm{III}} = z^{\mathrm{II}} > z^{\mathrm{I}}$ for $\delta = 1/2$.
[vii] $z^{\mathrm{VII}} > z^{\mathrm{VIII}} > z^{\mathrm{V}} > z^{\mathrm{VI}} > z^{\mathrm{IV}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $1/2 < k < \bar{\delta}_z^{58}(m)$.
[viii] $z^{\mathrm{VII}} > z^{\mathrm{VIII}} = z^{\mathrm{V}} > z^{\mathrm{VI}} > z^{\mathrm{IV}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for $\delta = \bar{\delta}_z^{58}(m)$.
[ix] $z^{\mathrm{VII}} > z^{\mathrm{V}} > z^{\mathrm{VIII}} > z^{\mathrm{VI}} > z^{\mathrm{IV}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $\bar{\delta}_z^{58}(m) < \delta < 1$.
[x] $z^{\mathrm{VII}} > z^{\mathrm{V}} > z^{\mathrm{VIII}} > z^{\mathrm{VI}} > z^{\mathrm{IV}} = z^{\mathrm{II}} > z^{\mathrm{III}} = z^{\mathrm{I}}$ for $\delta = 1$.

(6) When $t = (1/12)A$, then
[i] $z^{\mathrm{VII}} > z^{\mathrm{VIII}} > z^{\mathrm{IV}} > z^{\mathrm{V}} > z^{\mathrm{VI}} > z^{\mathrm{III}} > z^{\mathrm{II}} > z^{\mathrm{I}}$ for all $0 \leq \delta < \bar{\delta}_z^{45}(m = 1/12)$.
[ii] $z^{\mathrm{VII}} > z^{\mathrm{VIII}} > z^{\mathrm{V}} = z^{\mathrm{IV}} > z^{\mathrm{VI}} > z^{\mathrm{III}} > z^{\mathrm{II}} > z^{\mathrm{I}}$ for $\delta = \bar{\delta}_z^{45}(m = 1/12)$.
[iii] $z^{\mathrm{VII}} > z^{\mathrm{VIII}} > z^{\mathrm{V}} > z^{\mathrm{IV}} > z^{\mathrm{VI}} > z^{\mathrm{III}} > z^{\mathrm{II}} > z^{\mathrm{I}}$ for all $\bar{\delta}_z^{45}(m = 1/12) < \delta < \bar{\delta}_z^{46}(m = 1/12)$.
[iv] $z^{\mathrm{VII}} > z^{\mathrm{VIII}} > z^{\mathrm{V}} > z^{\mathrm{IV}} = z^{\mathrm{VI}} > z^{\mathrm{III}} = z^{\mathrm{II}} > z^{\mathrm{I}}$ for$\delta = \bar{\delta}_z^{46}(m = 1/12) = 1/2$.
[v] $z^{\mathrm{VII}} > z^{\mathrm{VIII}} > z^{\mathrm{V}} > z^{\mathrm{VI}} > z^{\mathrm{IV}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $1/2 < \delta < \bar{\delta}_z^{58}(m = 1/12)$.
[vi] $z^{\mathrm{VII}} > z^{\mathrm{VIII}} = z^{\mathrm{V}} > z^{\mathrm{VI}} > z^{\mathrm{IV}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for $\delta = \bar{\delta}_z^{58}(m = 1/12)$.
[vii] $z^{\mathrm{VII}} > z^{\mathrm{V}} > z^{\mathrm{VIII}} > z^{\mathrm{VI}} > z^{\mathrm{IV}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $\bar{\delta}_z^{58}(m = 1/12) < \delta < 1$.
[viii] $z^{\mathrm{VII}} > z^{\mathrm{V}} > z^{\mathrm{VIII}} > z^{\mathrm{VI}} > z^{\mathrm{IV}} = z^{\mathrm{II}} > z^{\mathrm{III}} = z^{\mathrm{I}}$ for $\delta = 1$.

(7) When $(1/12)A < t < (3/35)A$, then
[i] $z^{\mathrm{VII}} > z^{\mathrm{VIII}} > z^{\mathrm{IV}} > z^{\mathrm{V}} > z^{\mathrm{VI}} > z^{\mathrm{III}} > z^{\mathrm{II}} > z^{\mathrm{I}}$ for all $0 \leq \delta < \bar{\delta}_z^{45}(m)$.
[ii] $z^{\mathrm{VII}} > z^{\mathrm{VIII}} > z^{\mathrm{V}} = z^{\mathrm{IV}} > z^{\mathrm{VI}} > z^{\mathrm{III}} > z^{\mathrm{II}} > z^{\mathrm{I}}$ for $\delta = \bar{\delta}_z^{45}(m)$.
[iii] $z^{\mathrm{VII}} > z^{\mathrm{VIII}} > z^{\mathrm{V}} > z^{\mathrm{IV}} > z^{\mathrm{VI}} > z^{\mathrm{III}} > z^{\mathrm{II}} > z^{\mathrm{I}}$ for all $\bar{\delta}_z^{45}(m) < \delta < 1/2$.
[iv] $z^{\mathrm{VII}} > z^{\mathrm{VIII}} > z^{\mathrm{V}} > z^{\mathrm{IV}} > z^{\mathrm{VI}} > z^{\mathrm{III}} = z^{\mathrm{II}} > z^{\mathrm{I}}$ for$\delta = 1/2$.
[v] $z^{\mathrm{VII}} > z^{\mathrm{VIII}} > z^{\mathrm{V}} > z^{\mathrm{IV}} > z^{\mathrm{VI}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $1/2 < \delta < \bar{\delta}_z^{46}(m)$.
[vi] $z^{\mathrm{VII}} > z^{\mathrm{VIII}} > z^{\mathrm{V}} > z^{\mathrm{IV}} = z^{\mathrm{VI}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for $\delta = \bar{\delta}_z^{46}(m)$.
[vii] $z^{\mathrm{VII}} > z^{\mathrm{VIII}} > z^{\mathrm{V}} > z^{\mathrm{VI}} > z^{\mathrm{IV}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $\bar{\delta}_z^{46}(m) < \delta < \bar{\delta}_z^{58}(m)$.
[viii] $z^{\mathrm{VII}} > z^{\mathrm{VIII}} = z^{\mathrm{V}} > z^{\mathrm{VI}} > z^{\mathrm{IV}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for $\delta = \bar{\delta}_z^{58}(m)$.
[ix] $z^{\mathrm{VII}} > z^{\mathrm{V}} > z^{\mathrm{VIII}} > z^{\mathrm{VI}} > z^{\mathrm{IV}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $\bar{\delta}_z^{58}(m) < \delta < 1$.
[x] $z^{\mathrm{VII}} > z^{\mathrm{V}} > z^{\mathrm{VIII}} > z^{\mathrm{VI}} > z^{\mathrm{IV}} = z^{\mathrm{II}} > z^{\mathrm{III}} = z^{\mathrm{I}}$ for $\delta = 1$.

(8) When $t = (3/35)A$, then
[i] $z^{\mathrm{VII}} = z^{\mathrm{VIII}} > z^{\mathrm{IV}} > z^{\mathrm{V}} > z^{\mathrm{VI}} > z^{\mathrm{III}} > z^{\mathrm{II}} > z^{\mathrm{I}}$ for all $0 \leq \delta < \bar{\delta}_z^{45}(m = 3/35)(= \left(41 - \sqrt{1321}\right)/12)$.

[ii] $z^{\mathrm{VII}} = z^{\mathrm{VIII}} > z^{\mathrm{V}} = z^{\mathrm{IV}} > z^{\mathrm{VI}} > z^{\mathrm{III}} > z^{\mathrm{II}} > z^{\mathrm{I}}$ for $\delta = \bar{\delta}_z^{45}(m = 3/35)(= \left(41 - \sqrt{1321}\right)/12)$.
[iii] $z^{\mathrm{VII}} = z^{\mathrm{VIII}} > z^{\mathrm{V}} > z^{\mathrm{IV}} > z^{\mathrm{VI}} > z^{\mathrm{III}} > z^{\mathrm{II}} > z^{\mathrm{I}}$ for all $\bar{\delta}_z^{45}(m = 3/35)(= \left(41 - \sqrt{1321}\right)/12) < \delta < 1/2$.
[iv] $z^{\mathrm{VII}} = z^{\mathrm{VIII}} > z^{\mathrm{V}} > z^{\mathrm{IV}} > z^{\mathrm{VI}} > z^{\mathrm{III}} = z^{\mathrm{II}} > z^{\mathrm{I}}$ for $\delta = 1/2$.
[v] $z^{\mathrm{VII}} = z^{\mathrm{VIII}} > z^{\mathrm{V}} > z^{\mathrm{IV}} > z^{\mathrm{VI}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $1/2 < \delta < \bar{\delta}_z^{46}(m = 3/35)(= (13 - \sqrt{97})/6)$.
[vi] $z^{\mathrm{VII}} = z^{\mathrm{VIII}} > z^{\mathrm{V}} > z^{\mathrm{IV}} = z^{\mathrm{VI}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for $\delta = \bar{\delta}_z^{46}(m = 3/35)(= (13 - \sqrt{97})/6)$.
[vii] $z^{\mathrm{VII}} = z^{\mathrm{VIII}} > z^{\mathrm{V}} > z^{\mathrm{VI}} > z^{\mathrm{IV}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $\bar{\delta}_z^{46}(m = 3/35)(= (13 - \sqrt{97})/6) < \delta < 1$.
[viii] $z^{\mathrm{VII}} = z^{\mathrm{VIII}} = z^{\mathrm{V}} = z^{\mathrm{VI}} > z^{\mathrm{IV}} = z^{\mathrm{II}} > z^{\mathrm{III}} = z^{\mathrm{I}}$ for $\delta = 1$.

(9) When $(3/35)A < t < (5/53)A$, then
[i] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{IV}} > z^{\mathrm{V}} > z^{\mathrm{VI}} > z^{\mathrm{III}} > z^{\mathrm{II}} > z^{\mathrm{I}}$ for all $0 \leq \delta < \bar{\delta}_z^{45}(m)$.
[ii] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{V}} = z^{\mathrm{IV}} > z^{\mathrm{VI}} > z^{\mathrm{III}} > z^{\mathrm{II}} > z^{\mathrm{I}}$ for $\delta = \bar{\delta}_z^{45}(m)$.
[iii] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{V}} > z^{\mathrm{IV}} > z^{\mathrm{VI}} > z^{\mathrm{III}} > z^{\mathrm{II}} > z^{\mathrm{I}}$ for all $\bar{\delta}_z^{45}(m) < \delta < 1/2$.
[iv]$z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{V}} > z^{\mathrm{IV}} > z^{\mathrm{VI}} > z^{\mathrm{III}} = z^{\mathrm{II}} > z^{\mathrm{I}}$ for$\delta = 1/2$.
[v] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{V}} > z^{\mathrm{IV}} > z^{\mathrm{VI}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $1/2 < \delta < \bar{\delta}_z^{46}(m)$.
[vi] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{V}} > z^{\mathrm{IV}} = z^{\mathrm{VI}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $\delta = \bar{\delta}_z^{46}(m)$.
[vii] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{V}} > z^{\mathrm{VI}} > z^{\mathrm{IV}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $\bar{\delta}_z^{46}(m) < \delta < \bar{\delta}_z^{56}(m)$.
[viii] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{V}} = z^{\mathrm{VI}} > z^{\mathrm{IV}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for $\delta = \bar{\delta}_z^{56}(m)$.
[ix] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{VI}} > z^{\mathrm{V}} > z^{\mathrm{IV}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $\bar{\delta}_z^{56}(m) < \delta < \bar{\delta}_z^{67}(m)$.
[x] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} = z^{\mathrm{VI}} > z^{\mathrm{V}} > z^{\mathrm{IV}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for $\delta = \bar{\delta}_z^{67}(m)$.
[xi] $z^{\mathrm{VIII}} > z^{\mathrm{VI}} > z^{\mathrm{VII}} > z^{\mathrm{V}} > z^{\mathrm{IV}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $\bar{\delta}_z^{67}(m) < \delta < 1$.
[xii] $z^{\mathrm{VIII}} > z^{\mathrm{VI}} > z^{\mathrm{VII}} > z^{\mathrm{V}} > z^{\mathrm{IV}} = z^{\mathrm{II}} > z^{\mathrm{III}} = z^{\mathrm{I}}$ for $\delta = 1$.

(10) When $t = (5/53)A$, then
[i] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{IV}} > z^{\mathrm{V}} > z^{\mathrm{VI}} > z^{\mathrm{III}} > z^{\mathrm{II}} > z^{\mathrm{I}}$ for all $0 \leq \delta < 1/2$.
[ii] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{V}} = z^{\mathrm{IV}} > z^{\mathrm{VI}} > z^{\mathrm{III}} = z^{\mathrm{II}} > z^{\mathrm{I}}$ for $\delta = 1/2(= \bar{\delta}_z^{45}(m = 5/53))$.
[iii] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{V}} > z^{\mathrm{IV}} > z^{\mathrm{VI}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $1/2 < \delta < \bar{\delta}_z^{46}(m = 5/53)$.
[iv] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{V}} > z^{\mathrm{IV}} = z^{\mathrm{VI}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for $\delta = \bar{\delta}_z^{46}(m = 5/53)$.
[v] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{V}} > z^{\mathrm{VI}} > z^{\mathrm{IV}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $\bar{\delta}_z^{46}(m = 5/53) < \delta < \bar{\delta}_z^{56}(m = 5/53)$.
[vi] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{V}} = z^{\mathrm{VI}} > z^{\mathrm{IV}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for $\delta = \bar{\delta}_z^{56}(m = 5/53)$.
[vii] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{VI}} > z^{\mathrm{V}} > z^{\mathrm{IV}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$for all $\bar{\delta}_z^{56}(m) < \delta < \bar{\delta}_z^{67}(m = 5/53)$.
[viii] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} = z^{\mathrm{VI}} > z^{\mathrm{V}} > z^{\mathrm{IV}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for $\delta = \bar{\delta}_z^{67}(m = 5/53)$.
[ix] $z^{\mathrm{VIII}} > z^{\mathrm{VI}} > z^{\mathrm{VII}} > z^{\mathrm{V}} > z^{\mathrm{IV}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $\bar{\delta}_z^{67}(m) < \delta < 1$.
[x] $z^{\mathrm{VIII}} > z^{\mathrm{VI}} > z^{\mathrm{VII}} > z^{\mathrm{V}} > z^{\mathrm{IV}} = z^{\mathrm{II}} > z^{\mathrm{III}} = z^{\mathrm{I}}$ for $\delta = 1$.

(11) When $(5/53)A < t < (1/8)A$, then
[i] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{IV}} > z^{\mathrm{V}} > z^{\mathrm{VI}} > z^{\mathrm{III}} > z^{\mathrm{II}} > z^{\mathrm{I}}$ for all $0 \leq \delta < 1/2$.
[ii] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{IV}} > z^{\mathrm{V}} > z^{\mathrm{VI}} > z^{\mathrm{III}} = z^{\mathrm{II}} > z^{\mathrm{I}}$ for $\delta = 1/2$.
[iii] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{IV}} > z^{\mathrm{V}} > z^{\mathrm{VI}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $1/2 < \delta < \bar{\delta}_z^{45}(m)$.
[iv] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{IV}} = z^{\mathrm{V}} > z^{\mathrm{VI}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for $\delta = \bar{\delta}_z^{45}(m)$.
[v] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{V}} > z^{\mathrm{IV}} > z^{\mathrm{VI}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $\bar{\delta}_z^{45}(m) < \delta < \bar{\delta}_z^{46}(m)$.
[vi] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{V}} > z^{\mathrm{IV}} = z^{\mathrm{VI}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for $\delta = \bar{\delta}_z^{46}(m)$.

[vii] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{V}} > z^{\mathrm{VI}} > z^{\mathrm{IV}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $\bar{\delta}_z^{46}(m) < \delta < \bar{\delta}_z^{56}(m)$.
[viii] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{V}} = z^{\mathrm{VI}} > z^{\mathrm{IV}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for $\delta = \bar{\delta}_z^{56}(m)$.
[ix] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{VI}} > z^{\mathrm{V}} > z^{\mathrm{IV}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $\bar{\delta}_z^{56}(m) < \delta < \bar{\delta}_z^{67}(m)$.
[x] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} = z^{\mathrm{VI}} > z^{\mathrm{V}} > z^{\mathrm{IV}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for $\delta = \bar{\delta}_z^{67}(m)$.
[xi] $z^{\mathrm{VIII}} > z^{\mathrm{VI}} > z^{\mathrm{VII}} > z^{\mathrm{V}} > z^{\mathrm{IV}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $\bar{\delta}_z^{67}(m) < \delta < 1$.
[xii] $z^{\mathrm{VIII}} > z^{\mathrm{VI}} > z^{\mathrm{VII}} > z^{\mathrm{V}} > z^{\mathrm{IV}} = z^{\mathrm{II}} > z^{\mathrm{III}} = z^{\mathrm{I}}$ for $\delta = 1$.

(12) When $t = (1/8)A$, then
[i] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{IV}} > z^{\mathrm{V}} > z^{\mathrm{VI}} > z^{\mathrm{III}} > z^{\mathrm{II}} > z^{\mathrm{I}}$ for all $0 \leq \delta < 1/2$.
[ii] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{IV}} > z^{\mathrm{V}} > z^{\mathrm{VI}} > z^{\mathrm{III}} = z^{\mathrm{II}} > z^{\mathrm{I}}$ for $\delta = 1/2$.
[iii] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{IV}} > z^{\mathrm{V}} > z^{\mathrm{VI}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $1/2 < \delta < 3/4$.
[iv] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{IV}} = z^{\mathrm{V}} = z^{\mathrm{VI}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for $\delta = 3/4(= \bar{\delta}_z^{45}(m = 1/8) = \bar{\delta}_z^{46}(m = 1/8) = \bar{\delta}_z^{56}(m = 1/8))$.
[v] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{VI}} > z^{\mathrm{V}} > z^{\mathrm{IV}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $3/4 < \delta < \bar{\delta}_z^{67}(m = 1/8)(= (3/248)(235 - \sqrt{24721})$.
[vi] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} = z^{\mathrm{VI}} > z^{\mathrm{V}} > z^{\mathrm{IV}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for $\delta = \bar{\delta}_z^{67}(m = 1/8)$.
[vii] $z^{\mathrm{VIII}} > z^{\mathrm{VI}} > z^{\mathrm{VII}} > z^{\mathrm{V}} > z^{\mathrm{IV}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $\bar{\delta}_z^{67}(m = 1/8) < \delta < 1$.
[viii] $z^{\mathrm{VIII}} > z^{\mathrm{VI}} > z^{\mathrm{VII}} > z^{\mathrm{V}} > z^{\mathrm{IV}} = z^{\mathrm{II}} > z^{\mathrm{III}} = z^{\mathrm{I}}$ for $\delta = 1$.

(13) When $(1/8)A < t < \widehat{m}A$, ($\widehat{m} \equiv \{m \,|z^{\mathrm{IV}} = z^{\mathrm{V}}, z^{\mathrm{VI}} = z^{\mathrm{VII}}, m \equiv t/A\}$, $\widehat{m} \approx 0.161457$)) then
[i] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{IV}} > z^{\mathrm{V}} > z^{\mathrm{VI}} > z^{\mathrm{III}} > z^{\mathrm{II}} > z^{\mathrm{I}}$ for all $0 \leq \delta < 1/2$.
[ii] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{IV}} > z^{\mathrm{V}} > z^{\mathrm{VI}} > z^{\mathrm{III}} = z^{\mathrm{II}} > z^{\mathrm{I}}$ for $\delta = 1/2$.
[iii] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{IV}} > z^{\mathrm{V}} > z^{\mathrm{VI}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $1/2 < \delta < \bar{\delta}_z^{56}(m)$.
[vi] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{IV}} > z^{\mathrm{V}} = z^{\mathrm{VI}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for $\delta = \bar{\delta}_z^{56}(m)$.
[v] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{IV}} > z^{\mathrm{VI}} > z^{\mathrm{V}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $\bar{\delta}_z^{56} < \delta < \bar{\delta}_z^{46}(m)$.
[vi] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{IV}} = z^{\mathrm{VI}} > z^{\mathrm{V}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for $\delta = \bar{\delta}_z^{46}(m)$.
[vii] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{VI}} > z^{\mathrm{IV}} > z^{\mathrm{V}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $\bar{\delta}_z^{46}(m) < \delta < \bar{\delta}_z^{45}(m)$.
[viii] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{VI}} > z^{\mathrm{IV}} = z^{\mathrm{V}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for $\delta = \bar{\delta}_z^{45}(m)$.
[ix] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{VI}} > z^{\mathrm{V}} > z^{\mathrm{IV}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $\bar{\delta}_z^{45}(m) < \delta < \bar{\delta}_z^{67}(m)$.
[x] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} = z^{\mathrm{VI}} > z^{\mathrm{V}} > z^{\mathrm{IV}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for $\delta = \bar{\delta}_z^{67}(m)$.
[xi] $z^{\mathrm{VIII}} > z^{\mathrm{VI}} > z^{\mathrm{VII}} > z^{\mathrm{V}} > z^{\mathrm{IV}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $\bar{\delta}_z^{67}(m) < \delta < 1$.
[xii] $z^{\mathrm{VIII}} > z^{\mathrm{VI}} > z^{\mathrm{VII}} > z^{\mathrm{V}} > z^{\mathrm{IV}} = z^{\mathrm{II}} > z^{\mathrm{III}} = z^{\mathrm{I}}$ for $\delta = 1$.

(14) When $t = \widehat{m}A$, then
[i] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{IV}} > z^{\mathrm{V}} > z^{\mathrm{VI}} > z^{\mathrm{III}} > z^{\mathrm{II}} > z^{\mathrm{I}}$ for all $0 \leq \delta < 1/2$.
[ii] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{IV}} > z^{\mathrm{V}} > z^{\mathrm{VI}} > z^{\mathrm{III}} = z^{\mathrm{II}} > z^{\mathrm{I}}$ for $\delta = 1/2$.
[iii] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{IV}} > z^{\mathrm{V}} > z^{\mathrm{VI}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $1/2 < \delta < \bar{\delta}_z^{56}(m = \widehat{m})(\approx 0.568295)$.
[iv] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{IV}} > z^{\mathrm{V}} = z^{\mathrm{VI}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for $\delta = \bar{\delta}_z^{56}(m = \widehat{m})$.
[v] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{IV}} > z^{\mathrm{VI}} > z^{\mathrm{V}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $\bar{\delta}_z^{56}(m = \widehat{m}) < \delta < \bar{\delta}_z^{46}(m)(\approx 0.832221)$.
[vi] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{IV}} = z^{\mathrm{VI}} > z^{\mathrm{V}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for $\delta = \bar{\delta}_z^{46}(m = \widehat{m})$.
[vii] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{VI}} > z^{\mathrm{IV}} > z^{\mathrm{V}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $\bar{\delta}_z^{46}(m = \widehat{m}) < \delta < \bar{\delta}_z^{45}(m = \widehat{m})(\approx 0.905215)$.

[viii] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} = z^{\mathrm{VI}} > z^{\mathrm{IV}} = z^{\mathrm{V}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for $\delta = \bar{\delta}_z^{45}(m =)$.
[ix] $z^{\mathrm{VIII}} > z^{\mathrm{VI}} > z^{\mathrm{VII}} > z^{\mathrm{V}} > z^{\mathrm{IV}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $\bar{\delta}_z^{45}(m = \widehat{m}) < \delta < 1$.
[x] $z^{\mathrm{VIII}} > z^{\mathrm{VI}} > z^{\mathrm{VII}} > z^{\mathrm{V}} > z^{\mathrm{IV}} = z^{\mathrm{II}} > z^{\mathrm{III}} = z^{\mathrm{I}}$ for $\delta = 1$.

(15) When $\widehat{m}A < t < (12/67)A$
[i] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{IV}} > z^{\mathrm{V}} > z^{\mathrm{VI}} > z^{\mathrm{III}} > z^{\mathrm{II}} > z^{\mathrm{I}}$ for all $0 \leq \delta < 1/2$.
[ii] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{IV}} > z^{\mathrm{V}} > z^{\mathrm{VI}} > z^{\mathrm{III}} = z^{\mathrm{II}} > z^{\mathrm{I}}$ for $\delta = 1/2$.
[iii] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{IV}} > z^{\mathrm{V}} > z^{\mathrm{VI}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $1/2 < \delta < \bar{\delta}_z^{56}(m)$.
[iv]$z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{IV}} > z^{\mathrm{V}} = z^{\mathrm{VI}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for $\delta = \bar{\delta}_z^{56}(m)$.
[v] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{IV}} > z^{\mathrm{VI}} > z^{\mathrm{V}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $\bar{\delta}_z^{56}(m) < \delta < \bar{\delta}_z^{46}(m)$.
[vi] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{IV}} = z^{\mathrm{VI}} > z^{\mathrm{V}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for $\delta = \bar{\delta}_z^{46}(m)$.
[vii] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{VI}} > z^{\mathrm{IV}} > z^{\mathrm{V}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $\bar{\delta}_z^{46}(m) < \delta < \bar{\delta}_z^{67}(m)$.
[viii] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} = z^{\mathrm{VI}} > z^{\mathrm{IV}} > z^{\mathrm{V}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for $\delta = \bar{\delta}_z^{67}(m)$.
[ix] $z^{\mathrm{VIII}} > z^{\mathrm{VI}} > z^{\mathrm{VII}} > z^{\mathrm{IV}} > z^{\mathrm{V}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $\bar{\delta}_z^{67}(m) < \delta < \bar{\delta}_z^{45}(m)$.
[x] $z^{\mathrm{VIII}} > z^{\mathrm{VI}} > z^{\mathrm{VII}} > z^{\mathrm{IV}} = z^{\mathrm{V}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for $\delta = \bar{\delta}_z^{45}(m)$.
[xi] $z^{\mathrm{VIII}} > z^{\mathrm{VI}} > z^{\mathrm{VII}} > z^{\mathrm{V}} > z^{\mathrm{IV}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $\bar{\delta}_z^{45}(m) < \delta < 1$.
[xii] $z^{\mathrm{VIII}} > z^{\mathrm{VI}} > z^{\mathrm{VII}} > z^{\mathrm{V}} > z^{\mathrm{IV}} = z^{\mathrm{II}} > z^{\mathrm{III}} = z^{\mathrm{I}}$ for $\delta = 1$.

(16) When $t = (12/67)A$, then
[i] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{IV}} > z^{\mathrm{V}} > z^{\mathrm{VI}} > z^{\mathrm{III}} > z^{\mathrm{II}} > z^{\mathrm{I}}$ for all $0 \leq \delta < 1/2$.
[ii] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{IV}} > z^{\mathrm{V}} = z^{\mathrm{VI}} > z^{\mathrm{III}} = z^{\mathrm{II}} > z^{\mathrm{I}}$ for $\delta = 1/2 = \bar{\delta}_z^{56}(m = 12/67)$.
[iii] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{IV}} > z^{\mathrm{VI}} > z^{\mathrm{V}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $1/2 < \delta < \bar{\delta}_z^{46}(m = 12/67) = \frac{281-\sqrt{39505}}{96}$.
[iv] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{IV}} = z^{\mathrm{VI}} > z^{\mathrm{V}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for $\delta = \bar{\delta}_z^{46}(m = 12/67)$.
[v] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{VI}} > z^{\mathrm{IV}} > z^{\mathrm{V}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $\bar{\delta}_z^{46}(m = 12/67) < \delta < \bar{\delta}_z^{67}(m = 12/67) = \frac{7445-\sqrt{27085129}}{2512}$.
[vi] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} = z^{\mathrm{VI}} > z^{\mathrm{IV}} > z^{\mathrm{V}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $\delta = \bar{\delta}_z^{67}(m = 12/67)$.
[vii] $z^{\mathrm{VIII}} > z^{\mathrm{VI}} > z^{\mathrm{VII}} > z^{\mathrm{IV}} > z^{\mathrm{V}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $\bar{\delta}_z^{67}(m = 12/67) < \delta < \bar{\delta}_z^{45}(m = 12/67) = \frac{401-\sqrt{95713}}{96}$.
[viii] $z^{\mathrm{VIII}} > z^{\mathrm{VI}} > z^{\mathrm{VII}} > z^{\mathrm{IV}} = z^{\mathrm{V}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for $\delta = \bar{\delta}_z^{45}(m = 12/67)$.
[ix] $z^{\mathrm{VIII}} > z^{\mathrm{VI}} > z^{\mathrm{VII}} > z^{\mathrm{V}} > z^{\mathrm{IV}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $\bar{\delta}_z^{45}(m = 12/67) < \delta < 1$.
[x] $z^{\mathrm{VIII}} > z^{\mathrm{VI}} > z^{\mathrm{VII}} > z^{\mathrm{V}} > z^{\mathrm{IV}} = z^{\mathrm{II}} > z^{\mathrm{III}} = z^{\mathrm{I}}$ for $\delta = 1$.

(17) When $(12/67)A < t < (1/5)A$, then
[i] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{IV}} > z^{\mathrm{V}} > z^{\mathrm{VI}} > z^{\mathrm{III}} > z^{\mathrm{II}} > z^{\mathrm{I}}$ for all $0 \leq \delta < \bar{\delta}_z^{56}(m)$.
[ii] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{IV}} > z^{\mathrm{V}} = z^{\mathrm{VI}} > z^{\mathrm{III}} > z^{\mathrm{II}} > z^{\mathrm{I}}$ for $\delta = \bar{\delta}_z^{56}(m)$.
[iii] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{IV}} > z^{\mathrm{VI}} > z^{\mathrm{V}} > z^{\mathrm{III}} > z^{\mathrm{II}} > z^{\mathrm{I}}$ for all $\bar{\delta}_z^{56}(m) < \delta < 1/2$.
[iv] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{IV}} > z^{\mathrm{VI}} > z^{\mathrm{V}} > z^{\mathrm{III}} = z^{\mathrm{II}} > z^{\mathrm{I}}$ for $\delta = 1/2$.
[v] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{IV}} > z^{\mathrm{VI}} > z^{\mathrm{V}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $1/2 < \delta < \bar{\delta}_z^{46}(m)$.

[vi] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{IV}} = z^{\mathrm{VI}} > z^{\mathrm{V}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for $\delta = \bar{\delta}_z^{46}(m)$.

[vii] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} > z^{\mathrm{VI}} > z^{\mathrm{IV}} > z^{\mathrm{V}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $\bar{\delta}_z^{46}(m) < \delta < \bar{\delta}_z^{67}(m)$.

[viii] $z^{\mathrm{VIII}} > z^{\mathrm{VII}} = z^{\mathrm{VI}} > z^{\mathrm{IV}} > z^{\mathrm{V}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for $\delta = \bar{\delta}_z^{67}(m)$.

[ix] $z^{\mathrm{VIII}} > z^{\mathrm{VI}} > z^{\mathrm{VII}} > z^{\mathrm{IV}} > z^{\mathrm{V}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $\bar{\delta}_z^{67}(m) < \delta < \bar{\delta}_z^{45}(m)$.

[x] $z^{\mathrm{VIII}} > z^{\mathrm{VI}} > z^{\mathrm{VII}} > z^{\mathrm{IV}} = z^{\mathrm{V}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for $\delta = \bar{\delta}_z^{45}(m)$.

[xi] $z^{\mathrm{VIII}} > z^{\mathrm{VI}} > z^{\mathrm{VII}} > z^{\mathrm{V}} > z^{\mathrm{IV}} > z^{\mathrm{II}} > z^{\mathrm{III}} > z^{\mathrm{I}}$ for all $\bar{\delta}_z^{45}(m) < \delta < 1$.

[xii] $z^{\mathrm{VIII}} > z^{\mathrm{VI}} > z^{\mathrm{VII}} > z^{\mathrm{V}} > z^{\mathrm{IV}} = z^{\mathrm{II}} > z^{\mathrm{III}} = z^{\mathrm{I}}$ for $\delta = 1$.

Appendix F:

Proof of Proposition 3:

First, we have $q^{\mathrm{I}} - q^{\mathrm{II}} = 0$, $q^{\mathrm{I}} - q^{\mathrm{III}} = 0$, $q^{\mathrm{I}} - q^{\mathrm{IV}} = 0$, $q^{\mathrm{II}} - q^{\mathrm{III}} = 0$, $q^{\mathrm{II}} - q^{\mathrm{IV}} = 0$, and $q^{\mathrm{III}} - q^{\mathrm{IV}} = 0$, which shows that $q^{\mathrm{I}} = q^{\mathrm{II}} = q^{\mathrm{III}} = q^{\mathrm{IV}}$.

Second, the following results are straightforwardly derived.

$$q^{\mathrm{IV}} - q^{\mathrm{VIII}} = \frac{A - t}{120} > 0, \tag{F.1}$$

$$q^{\mathrm{VIII}} - q^{\mathrm{VI}} = \frac{3(1-\delta)(A-t)}{40(6-\delta)} \geq 0, \tag{F.2}$$

$$q^{\mathrm{VI}} - q^{\mathrm{V}} = \frac{3[4(1-\delta)+5](A-t) + 8\delta(6-\delta)t}{8(6-\delta)(4\delta^2 - 42\delta + 63)} > 0, \tag{F.3}$$

$$q^{\mathrm{V}} - q^{\mathrm{VII}} = \frac{3(1-\delta)(A(\delta+3) + 5(12-\delta)t)}{25(4\delta^2 - 42\delta + 63)} \geq 0. \tag{F.4}$$

When $\delta = 1$, then $q^{\mathrm{VIII}} = q^{\mathrm{VI}}$ and $q^{\mathrm{V}} = q^{\mathrm{VII}}$. Thus, we obtain that $q^{\mathrm{I}} = q^{\mathrm{II}} = q^{\mathrm{III}} = q^{\mathrm{IV}} > q^{\mathrm{VIII}} \geq q^{\mathrm{VI}} > q^{\mathrm{V}} \geq q^{\mathrm{VII}}$.■

Appendix G:

Proof of Proposition 4:

Under the assumption of $A > 5t$, we readily obtain the following results:

$$e^{\mathrm{I}} - e^{\mathrm{VII}} = \frac{2A(3-\delta) + 5(3-2\delta)t}{15(3-\delta)} > 0, \tag{G.1}$$

$$e^{\mathrm{II}} - e^{\mathrm{VII}} = \frac{(1-\delta)(4A + 15t) + 2A - 5\delta t}{15(3-2\delta)} > 0, \tag{G.2}$$

$$e^{\mathrm{III}} - e^{\mathrm{VII}} = \frac{4A + 5t}{30} > 0, \tag{G.3}$$

$$e^{\mathrm{IV}} - e^{\mathrm{VII}} = \frac{2A - 5t}{15} > 0, \tag{G.4}$$

$$e^{\mathrm{V}} - e^{\mathrm{VII}} = \frac{(1-\delta)(A(12-\delta) + 15(9-\delta)t)}{5(63 - 42\delta + 4\delta^2)} \geq 0, \tag{G.5}$$

$$e^{\mathrm{VI}} - e^{\mathrm{VII}} = \frac{4(1-\delta)(9-\delta)A + 15(A - 5\delta)t + 5\big(4 + (1-\delta)(53 - 12\delta)\big)t}{40(6-\delta)(3-2\delta)} > 0, \tag{G.6}$$

$$e^{\mathrm{VIII}} - e^{\mathrm{VII}} = \frac{3A - 11t}{40} > 0, \tag{G.7}$$

$$e^{\mathrm{I}} - e^{\mathrm{II}} = \frac{\delta t}{(3-2\delta)(3-\delta)} \geq 0, \tag{G.8}$$

$$e^{\mathrm{I}} - e^{\mathrm{III}} = \frac{(1-\delta)t}{2(3-\delta)} \geq 0, \tag{G.9}$$

$$e^{\mathrm{I}} - e^{\mathrm{VI}} = \frac{(A-t)(3-\delta)(9-2\delta)(3-2\delta) + 24\delta(6-\delta)t}{24(6-\delta)(3-\delta)(3-2\delta)} > 0, \tag{G.10}$$

$$e^{\mathrm{I}} - e^{\mathrm{V}} = \frac{(6-\delta)((3-\delta)^2(A-t) + 9\delta t)}{3(3-\delta)(63-42\delta+4\delta^2)} > 0, \tag{G.11}$$

$$e^{\mathrm{I}} - e^{\mathrm{VI}} = \frac{(A-t)(3-\delta)(9-2\delta)(3-2\delta) + 24\delta(6-\delta)t}{24(6-\delta)(3-\delta)(3-2\delta)} > 0, \tag{G.12}$$

$$e^{\mathrm{I}} - e^{\mathrm{VIII}} = \frac{7A(3-\delta) + (219-113\delta)t}{120(3-\delta)} > 0, \tag{G.13}$$

Therefore, from (G.1)-(G.7), e^{VII} is smaller than that under any of the other seven scenarios if $\delta \in [0,1)$. On the other hand, from (G.1) and (G.8)-(G.13), e^{I} is larger than that under any of the other seven scenarios if $\delta \in (0,1)$. ■

Appendix H:

Proof of Proposition 5:

Under the assumption of $A > 5t$, we obtain the following results:

$$\pi^{\mathrm{VII}} - \pi^{\mathrm{I}} = \frac{1}{450}\left(4A^2 + 10At + \frac{25(6(6-\delta)(1-\delta) + \delta^2)t^2}{(3-\delta)^2}\right) > 0, \tag{H.1}$$

$$\pi^{\mathrm{VII}} - \pi^{\mathrm{II}} = \frac{2(1-\delta)(2A^2 + 5At + 75t^2) + 2A^2 + 5t(A - 5\delta t)}{225(3-2\delta)} > 0, \tag{H.2}$$

$$\pi^{\mathrm{VII}} - \pi^{\mathrm{III}} = \frac{(4A+5t)^2}{1800} > 0, \tag{H.3}$$

$$\pi^{\mathrm{VII}} - \pi^{\mathrm{IV}} = \frac{2A^2 + 5t(A-5t)}{225} > 0, \tag{H.4}$$

$$\pi^{\mathrm{VII}} - \pi^{\mathrm{V}} = \frac{(1-\delta)(A^2(3+\delta) + 10A(12-\delta)t + 75(9-\delta)t^2)}{50(63-42\delta+4\delta^2)} \geq 0, \tag{H.5}$$

$$\pi^{\mathrm{VII}} - \pi^{\mathrm{VI}} = \frac{4(1-\delta)((6+\delta)A^2 + 10(4-\delta)At + 75(6-\delta)t^2) + 5(3A^2 + At + 9t(A-5t))}{400(6-\delta)(3-2\delta)} > 0, \tag{H.6}$$

$$\pi^{\mathrm{VII}} - \pi^{\mathrm{VIII}} = \frac{3A^2 + 10At - 45t^2}{400}(3A^2 + 10At - 45t^2) > 0. \tag{H.7}$$

Thus, π^{VII} is larger than under any of the other seven scenarios if $\delta \in [0,1)$. ■

Appendix I:

Proof of Proposition 6:

After some manipulation, the equilibrium remuneration of the manager under each scenario is derived as follows.

$$V^{\mathrm{I}} = \frac{2A^2(3-\delta)^2 - 4A(3-\delta)^2 t + (45 - 12\delta + 2\delta^2)t^2}{(3-\delta)^2}, \tag{I.1}$$

$$V^{\mathrm{II}} = \frac{2A^2(3-2\delta) - 4A(3-2\delta)t + (15-4\delta)t^2}{18(3-2\delta)}, \tag{I.2}$$

$$V^{\mathrm{III}} = \frac{8A^2 - 16At + 35t^2}{72} \quad \text{(I.3)}$$

$$V^{\mathrm{IV}} = \frac{2A^2 - 4At + 11t^2}{18}, \quad \text{(I.4)}$$

$$V^{\mathrm{V}} = \frac{A^2(405 - 504\delta + 183\delta^2 - 14\delta^3) - 2A(3 + 2\delta)(9 - 15\delta + \delta^2)t + 9(6 - \delta)^2(3 + 2\delta)t^2}{2(63 - 42\delta + 4\delta^2)^2}, \quad \text{(I.5)}$$

$$V^{\mathrm{VI}} = \frac{A^2(3 - 2\delta)(93 - 14\delta) - 2A(3 - 2\delta)(69 - 10\delta)t + (711 - 300\delta + 28\delta^2)t^2}{32(6 - \delta)^2(3 - 2\delta)}, \quad \text{(I.6)}$$

$$V^{\mathrm{VII}} = \frac{14A^2 + 10At + 225t^2}{250}, \quad \text{(I.7)}$$

$$V^{\mathrm{VIII}} = \frac{79A^2 - 118At + 439t^2}{800}. \quad \text{(I.8)}$$

From (H.1)-(H.8), we obtain the following results.[26]

$$V^{\mathrm{IV}} - V^{\mathrm{I}} = \frac{(6(1 - \delta) + \delta^2)t^2}{2(3 - \delta)^2} > 0, \quad \text{(I.9)}$$

$$V^{\mathrm{IV}} - V^{\mathrm{II}} = \frac{(1 - \delta)t^2}{3 - 2\delta} \geq 0, \quad \text{(I.10)}$$

$$V^{\mathrm{IV}} - V^{\mathrm{III}} = \frac{t^2}{8} > 0, \quad \text{(I.11)}$$

$$V^{\mathrm{VII}} - V^{\mathrm{V}} = \frac{(1 - \delta)\Delta_1}{250(63 - 42\delta + 4\delta^2)^2} \geq 0, \quad \text{(I.12)}$$

$$V^{\mathrm{VIII}} - V^{\mathrm{VI}} = \frac{(1 - k)\Delta_2}{800(6 - \delta)^2(3 - 2\delta)} \geq 0. \quad \text{(I.13)}$$

Equations (I.9)-(I.13) imply that equilibrium remuneration under scenarios I, II, III, V, and VI is smaller than that in at least one of the other scenarios. Thus, we proceed with the comparison among V^{IV}, V^{VII}, and V^{VIII}.

We obtain the results of the comparison among V^{IV}, V^{VII}, and V^{VIII} as follows.

[i] $V^{\mathrm{IV}} > V^{\mathrm{VIII}} > V^{\mathrm{VII}}$ for all $0 \leq t < 3(-125 + 93\sqrt{5})A/1405$.

[ii] $V^{\mathrm{IV}} > V^{\mathrm{VIII}} = V^{\mathrm{VII}}$ for $t = 3(-125 + 93\sqrt{5})A/1405$.

[iii] $V^{\mathrm{IV}} > V^{\mathrm{VII}} > V^{\mathrm{VIII}}$ for all $3(-125 + 93\sqrt{5})A/1405 < t < (-59 + 3\sqrt{745})A/130$.

[iv] $V^{\mathrm{IV}} = V^{\mathrm{VII}} > V^{\mathrm{VIII}}$ for $t = (-59 + 3\sqrt{745})A/130$.

[v] $V^{\mathrm{VII}} > V^{\mathrm{IV}} > V^{\mathrm{VIII}}$ for all $(-59 + 3\sqrt{745})A/130 < t < (89/449)A$.

[vi] $V^{\mathrm{VII}} > V^{\mathrm{IV}} = V^{\mathrm{VIII}}$ for $t = (89/449)A$.

[vii] $V^{\mathrm{VII}} > V^{\mathrm{VIII}} > V^{\mathrm{IV}}$ for $(89/449)A < t < A/5$.

Therefore, when $0 \leq t < (-59 + 3\sqrt{745})A/130$, the remuneration of managers under scenario IV is greater than that under any of the other seven scenarios. On the other hand, when $(-59 + 3\sqrt{745})A/130 < t < A/5$, the remuneration of managers under scenario VII is greater than that under any of the other seven scenarios.

■

[26] In (I.12) and (I.13), $\Delta_1 \equiv A^2(1300 + 2506(1 - \delta)^2 + (1135 + 224\delta^2)(1 - \delta)) + 10A(12 - \delta)(387 - 78\delta + 16\delta^2)t + 225(1700 + 314(1 - \delta)^2 + (1415 + 16\delta^2)(1 - \delta))t^2 > 0$. Furthermore, because $11 - 17m + 506m^2 > 0, 959 - 1478m + 8519m^2 > 0,$ and $79 - 118m + 439m^2 > 0$ for all $m \in (0,1/5)$,($m \equiv t/A$),$\Delta_2 \equiv 40(11 - 17m + 506m^2) + (1 - \delta)(959 - 1478m + 8519m^2) + 2(1 - \delta)^2(79 - 118m + 439m^2) > 0$.

Appendix J:

(1) First, we straightforwardly have

$$W^{\mathrm{III}} - W^{\mathrm{I}} = \frac{(1-\delta)(4d(3-\delta) + (3+\delta)t)t}{4(3-\delta)^2} \geq 0. \tag{J.1}$$

This result implies that W^{I} is less than social welfare in scenario III. Furthermore, we obtain

$$W^{\mathrm{III}} - W^{\mathrm{II}} = \frac{t\big((1-\delta)(4d+t) + \delta(3t-4d)\big)}{4(3-2\delta)}, \tag{J.2}$$

$$W^{\mathrm{IV}} - W^{\mathrm{II}} = \frac{2(1-\delta)(2d-t)t}{3-2\delta}. \tag{J.3}$$

From (J.2), if at least $d < (3/4)t$, then $W^{\mathrm{III}} > W^{\mathrm{II}}$. In addition, from (J.3), when $d > t/2$ and $0 \leq \delta < 1$, $W^{\mathrm{IV}} > W^{\mathrm{II}}$. Thus, W^{I} and W^{II} are dominated by the other scenarios for all $d > 0, A > 0, \delta \in [0,1]$ and $t \in [0,20)$.

(2) Next, we focus on W^{V}. After some manipulations, we obtain

$$W^{\mathrm{VII}} - W^{\mathrm{V}} = \frac{(1-\delta)U_1}{25(63-42\delta+4\delta^2)^2}, \tag{J.4}$$

$$W^{\mathrm{III}} - W^{\mathrm{V}} = \frac{U_2}{36(63-42\delta+4\delta^2)^2}. \tag{J.5}$$

Therein, $U_1 \equiv -400(3+\delta)(3771-2514\delta+218\delta^2) + 50d(63-42\delta+4\delta^2)(20(12-\delta)+3(9-\delta)t) + 720(-1674+1308\delta-220\delta^2+11\delta^3)t + 3(-8991+7497\delta-1380\delta^2+74\delta^3)t^2$ and $U_2 \equiv 40000(3-\delta)^2(171-114\delta+10\delta^2) + 800(1863-1512\delta+324\delta^2-42\delta^3+2\delta^4)t - (9153-31644\delta+21384\delta^2-3768\delta^3+200\delta^4)t^2 - 12d(63-42\delta+4\delta^2)(200(6-\delta)(3-\delta)-(99-138\delta+14\delta^2)t)$. Here, we define $d_{U1}(t,\delta) \equiv \{d(>0) | U_1 = 0, A > 0, 0 \leq t < 20,$ and $0 \leq \delta \leq 1\}$ and $d_{U2}(t,\delta) \equiv \{d(>0) | U_2 = 0, A > 0, 0 \leq t < 20,$ and $0 \leq \delta \leq 1\}$. If $d > d_{U1}\big(t = 20, \delta = \overline{\delta} \approx 0.5828\big) \approx 16.1891$, then $W^{\mathrm{VII}} > W^{\mathrm{V}}$ for all $t \in [0,20)$.[27] Furthermore, when $0 < d < d_{U2}(t = 0, \delta = 1) = 268/15$ (≈ 17.8666), then $W^{\mathrm{III}} > W^{\mathrm{V}}$ for all $\delta \in [0,1]$ and $t \in [0,20)$. Therefore, W^{V} is dominated by the other scenarios for all $d > 0$ and $t \in [0,20)$.

(3) Finally, we prove that W^{VI} is smaller than social welfare in other scenarios. The values of $W^{\mathrm{VIII}} - W^{\mathrm{VI}}$ and $W^{\mathrm{III}} - W^{\mathrm{VI}}$ are obtained as follows:

$$W^{\mathrm{VIII}} - W^{\mathrm{VI}} = \frac{Y_1(1-\delta)}{800(6-\delta)^2(3-2\delta)}, \tag{J.6}$$

$$W^{\mathrm{III}} - W^{\mathrm{VI}} = \frac{Y_2}{288(6-\delta)^2(3-2\delta)}, \tag{J.7}$$

where $Y_1 \equiv A^2(1017-825\delta+98\delta^2) - 2A(3-2\delta)(20d(6-\delta)+(219-29\delta)t) + t(40d(2898-975\delta+82\delta^2)+(-57303+18975\delta-1582\delta^2)t)$ and $Y_2 \equiv A^2(3-2\delta)^2(69-10\delta) - 24Ad(3-2\delta)(54-21\delta+2\delta^2) + 2A(21-2\delta)^2(3-2\delta)t - 24d(-594+1179\delta-348\delta^2+28\delta^3)t - (675-7506\delta+2412\delta^2-200\delta^3)t^2$. Here, let us define $d_{Y1}(t,\delta) \equiv \{d(>0) | Y_1 = 0, A > 0, 0 \leq t < 20,$ and $0 \leq \delta \leq 1\}$ and $d_{Y2}(t,\delta) \equiv \{d(>0) | Y_2 = 0, A > 0, 0 \leq t < 20,$ and $0 \leq \delta \leq 1\}$.

Then, $d_{Y1}(t,\delta)$ is derived as

$$d_{Y1}(t,\delta) = \frac{10000(3-2\delta)(339-49\delta) - 200(3-2\delta)(219-29\delta)t - (57303-18975\delta+1582\delta^2)t^2}{40(6-\delta)(100(3-2\delta)-(483-82\delta)t)}. \tag{J.8}$$

[27] $\overline{\delta}$ is derived from $\partial d_1(t = 20, \delta)/\partial\delta = 0$.

Because $\partial d_{Y1}(t,\delta)/\partial t > 0$ and $\partial d_{Y1}(t,\delta)/\partial \delta > 0$, $W^{\mathrm{VIII}} > W^{\mathrm{VI}}$ for all $t \in [0,20)$ if $d > d_{Y1}(t = 20, \delta = 1) = 96/11 \approx 8.7227$. Moreover, by solving $d_{Y1}(t, \delta = 1) = 0$ with respect to t, we obtain the critical tax rate $\bar{t}_1 \equiv 100\left(-19 + 30\sqrt{129}\right)/3991 \approx 8.0615$. Thus, if $t < \bar{t}_1$, then $W^{\mathrm{VIII}} > W^{\mathrm{VI}}$ for all $d > 0$.

In addition, $d_{Y2}(t,\delta)$ is derived as

$$d_{Y2}(t,\delta) = \frac{10000(3-2\delta)^2(69-10\delta) + 200(21-2\delta)^2(3-2\delta)t - (675 - 7506\delta + 2412\delta^2 - 200\delta^3)t^2}{24(6-\delta)(100(9-2\delta)(3-2\delta) - (99 - 180\delta + 28\delta^2)t)}. \tag{J.9}$$

We readily have that $\partial d_{Y2}(t,\delta)/\partial t > 0$ and $\partial d_{Y2}(t,\delta)/\partial \delta < 0$. Hence, if $d < d_{Y2}(t = 0, \delta = 1) = 295/42 \approx 7.023$, then $W^{\mathrm{III}} > W^{\mathrm{VI}}$ for all $t \in [0,20)$. In addition, by solving $d_{Y2}(t, \delta = 1) = 96/11$ with respect to t, the critical tax rate is derived as $\bar{t}_2 = 20(-4591 + 6\sqrt{6139186})/50809 \approx 4.0447$. Therefore, if $t > \bar{t}_2$, then $W^{\mathrm{III}} > W^{\mathrm{VI}}$ for all $d \in (0, 96/11]$.

From the analysis above, the value of W^{VI} is dominated by the other scenarios for all $d > 0$ and $t \in [0,20)$.

Appendix K:

First, we straightforwardly have that, for all $d > 0$, $\delta \in [0,1]$ and $t \in [0,20)$,

$$NCS^{\mathrm{II}} - NCS^{\mathrm{I}} = \frac{2d\delta t}{(3-2\delta)(3-\delta)} \geq 0, \tag{K.1}$$

$$NCS^{\mathrm{III}} - NCS^{\mathrm{II}} = \frac{d(1-2\delta)t}{3-2\delta} \gtreqless 0, \tag{K.2}$$

$$NCS^{\mathrm{IV}} - NCS^{\mathrm{II}} = \frac{4d(1-\delta)t}{3-2\delta} \geq 0, \tag{K.3}$$

$$NCS^{\mathrm{IV}} - NCS^{\mathrm{III}} = \frac{dt}{2} \geq 0. \tag{K.4}$$

Thus, NCS^{I}, NCS^{II}, and NCS^{III} are (weakly) dominated by scenario IV.

Furthermore, we easily obtain the following:

$$NCS^{\mathrm{IV}} - NCS^{\mathrm{V}} = \frac{2H_1(d,t,\delta)}{9(63-42\delta+4\delta^2)^2} \lesseqgtr 0, \tag{K.5}$$

$$NCS^{\mathrm{VII}} - NCS^{\mathrm{V}} = \frac{2(1-\delta)H_2(d,t,\delta)}{25(63-42\delta+4\delta^2)^2} \lesseqgtr 0, \tag{K.6}$$

$$NCS^{\mathrm{VII}} - NCS^{\mathrm{VI}} = \frac{H_3(d,t,\delta)}{800(6-\delta)^2(3-2\delta)} \lesseqgtr 0, \tag{K.7}$$

$$NCS^{\mathrm{VIII}} - NCS^{\mathrm{VI}} = \frac{(1-\delta)H_4(d,t,\delta)}{800(6-\delta)^2(3-2\delta)} \lesseqgtr 0. \tag{K.8}$$

Therein, $H_1(d,t,\delta) \equiv (100(3-\delta)^2 - (9 - 15\delta + \delta^2)t)(100(117 - 78\delta + 7\delta^2) - (117 - 69\delta + 7\delta^2)t) - 3d(63 - 42\delta + 4\delta^2)(100(6-\delta)(3-\delta) - (144 - 132\delta + 13\delta^2)t)$, $H_2(d,t,\delta) \equiv -1200(3+\delta)(891 - 594\delta + 53\delta^2) - 360(1674 - 1308\delta + 220\delta^2 - 11\delta^3)t + 3(12-\delta)(216 - 129\delta + 13\delta^2)t^2 + 25d(63 - 42\delta + 4\delta^2)(20(12-\delta) + 3(9-\delta)t)$, $H_3(d,t,\delta) \equiv 200d(6-\delta)(20(17-2\delta)(3-2\delta) + (57 - 80\delta + 12\delta^2)t) - 3(3-2\delta)(400(13+2\delta)(711-106\delta) + 40(1377 - 1084\delta + 132\delta^2)t - (7 - 2\delta)(171 - 26\delta)t^2)$, $H_4(d,t,\delta) \equiv 3(459 - 375\delta + 46\delta^2)(100-t)^2 - 40d(6-\delta)(100(3-2\delta) - (483 - 82\delta)t)$.

Here, we define $d_1(t,\delta) \equiv \{d | H_1(d,t,\delta) = 0, d > 0, \delta \in [0,1], t \in [0,20)\}$. Then, we obtain $d_1(t,\delta)$ as

$$d_1(t,\delta) = \frac{(100(3-\delta)^2 - (9-15\delta+\delta^2)t)(100(117-78\delta+7\delta^2) - (117-69\delta+7\delta^2)t)}{3(63-42\delta+4\delta^2)(100(6-\delta)(3-\delta) - (144-132\delta+13\delta^2)t)}. \tag{K.9}$$

$d_1(t,\delta)$ has the minimum value at $(t,\delta) = (0,1)$. Thus, if $d < d_1(0,1) = 368/15$, then $H_1(d,t,\delta) > 0$ for all $\delta \in [0,1]$ and $t \in [0,20)$. This implies that $NCS^{\mathrm{IV}} > NCS^{\mathrm{V}}$ for all $d \in (0, 368/15)$, $\delta \in [0,1]$ and $t \in [0,20)$. Furthermore, when we define that $d_2(t,\delta) \equiv \{d | H_2(d,t,\delta) = 0, d > 0, \delta \in [0,1], t \in [0,20)\}$, we have

$$d_2(t,\delta) = \frac{3(20(3+2\delta) + (12-\delta)t)(20(891-594\delta+53\delta^2) - (216-129\delta+13\delta^2)t)}{25(63-42\delta+4\delta^2)(20(12-\delta) + 3(9-\delta)t)}. \tag{K.10}$$

Then, $d_2(t,\delta)$ reaches the maximum value at $(t,\delta) = (0,1)$. Thus, if $d > d_2(0,1) = 168/11$, $H_2(d,t,\delta) > 0$ for all $\delta \in [0,1]$ and $t \in [0,20)$. This implies that $NCS^{\mathrm{VII}} > NCS^{\mathrm{V}}$ for all $d > 168/11$, $\delta \in [0,1]$ and $t \in [0,20)$. Hence, $max\{NCS^{\mathrm{IV}}, NCS^{\mathrm{VII}}\} > NCS^{\mathrm{V}}$ for all $d > 0$, $\delta \in [0,1]$ and $t \in [0,20)$.

Next, when we define that $d_3(t,\delta) \equiv \{d | H_3(d,t,\delta) = 0, d > 0, \delta \in [0,1], t \in [0,20)\}$, we have

$$d_3(t,\delta) = \frac{3(3-2\delta)(400(13+2\delta)(711-106\delta) + 40(1377-1084\delta+132\delta^2)t - (7-2\delta)(171-26\delta)t^2)}{200(6-\delta)(20(17-2\delta)(3-2\delta) + (57-80\delta+12\delta^2)t)}. \tag{K.11}$$

It is straightforward to show that $\partial d_3(t,\delta)/\partial\delta > 0$ for all $\delta \in [0,1]$ and $t \in [0,20)$. Thus, $d_3(t,\delta) \leq d_3(t,1) = \frac{3(60+t)(2420-29t)}{40(300-11t)}$. Furthermore, $d_3(t,1)$ is increasing in $t \in [0,20)$. As a result, we have $d_3(t,\delta) \leq d_3(t,1) = \frac{3(60+t)(2420-29t)}{40(300-11t)} < d_3(20,1) = 138$. This result shows that $H_3(d,t,\delta) > 0$ for all $\delta \in [0,1]$ and $t \in [0,20)$ if $d > 138$. Therefore, $NCS^{\mathrm{VII}} - NCS^{\mathrm{VI}}$ for all $d > 138$, $\delta \in [0,1]$ and $t \in [0,20)$. In addition, we define $d_4(t,\delta) \equiv \{d | H_4(d,t,\delta) = 0, d > 0, \delta \in [0,1], t \in [0,20)\}$. Then, we can derive $d_4(t,\delta)$ explicitly as

$$d_4(t,\delta) = \frac{3(3-2\delta)(153-23\delta)(100-t)^2}{40(6-\delta)(100(3-2\delta) - (483-82\delta)t)}. \tag{K.12}$$

We find that if $d < d_4(0,0) = 765/4$, $H_4(d,t,\delta) > 0$ for all $\delta \in [0,1]$ and $t \in [0,20)$. Therefore, $NCS^{\mathrm{VIII}} - NCS^{\mathrm{VI}}$ for all $d \in (0, 765/4)$, $\delta \in [0,1]$ and $t \in [0,20)$. From the comparison results above, $max\{NCS^{\mathrm{VII}}, NCS^{\mathrm{VIII}}\} > NCS^{\mathrm{VI}}$ for all $d > 0$, $\delta \in [0,1]$ and $t \in [0,20)$.

Consequently, NCS^{V} and NCS^{VI} are dominated by other scenarios.

Appendix L:

Table A2(I): Extended equilibrium outcome under Scenario I

	Noncooperative ECSR and noncooperative environmental R&D
ECSR level	$\hat{\theta}^{\mathrm{I}} = 0$
Environmental R&D effort	$\hat{z}^{\mathrm{I}} = \frac{3d(6-\delta) - 100(3-\delta)}{45-30\delta+2\delta^2}$
Output	$\hat{q}^{\mathrm{I}} = \frac{100(18-12\delta+\delta^2) - d(6-\delta)(3-\delta)}{45-30\delta+2\delta^2}$
Pollution emission	$\hat{e}^{\mathrm{I}} = \frac{100(21-13\delta+\delta^2) - d(6-\delta)^2}{45-30\delta+2\delta^2}$
Profit	$\hat{\pi}^{\mathrm{I}} = (\hat{q}^{\mathrm{I}})^2 + \hat{t}^{\mathrm{I}}\hat{z}^{\mathrm{I}} - (3/2)(\hat{z}^{\mathrm{I}})^2 + \delta(\hat{z}^{\mathrm{I}})^2$
Social welfare	$\widehat{W}^{\mathrm{I}} = 2(\hat{q}^{\mathrm{I}})^2 + 2\hat{\pi}^{\mathrm{I}} + 2\hat{t}^{\mathrm{I}}\hat{e}^{\mathrm{I}} - 2d\hat{e}^{\mathrm{I}}$

Table A2(II): Extended equilibrium outcome under Scenario II

	Noncooperative ECSR and cooperative environmental R&D
ECSR level	$\hat{\theta}^{\mathrm{II}} = 0$
Environmental R&D effort	$\hat{z}^{\mathrm{II}} = \dfrac{6d(3-\delta) - 100(3-2\delta)}{45 - 42\delta + 8\delta^2}$
Output	$\hat{q}^{\mathrm{II}} = \dfrac{2(100-d)(3-\delta)}{15-4\delta}$
Pollution emission	$\hat{e}^{\mathrm{II}} = \dfrac{100(21 - 20\delta + 4\delta^2) - 4d(\delta-3)^2}{45 - 42\delta + 8\delta^2}$
Profit	$\hat{\pi}^{\mathrm{II}} = (\hat{q}^{\mathrm{II}})^2 + \hat{t}^{\mathrm{II}}\hat{z}^{\mathrm{II}} - (3/2)(\hat{z}^{\mathrm{II}})^2 + \delta(\hat{z}^{\mathrm{II}})^2$
Social welfare	$\widehat{W}^{\mathrm{II}} = 2(\hat{q}^{\mathrm{II}})^2 + 2\hat{\pi}^{\mathrm{II}} + 2\hat{t}^{\mathrm{II}}\,\hat{e}^{\mathrm{II}} - 2d\hat{e}^{\mathrm{II}}$

Table A2(III): Extended equilibrium outcome under Scenario III

	Noncooperative ECSR and ERJV competition
ECSR level	$\hat{\theta}^{\mathrm{III}} = 0$
Environmental R&D effort	$\hat{z}^{\mathrm{III}} = \dfrac{5}{17}(3d - 40)$
Output	$\hat{q}^{\mathrm{III}} = \dfrac{10}{17}(70 - d)$
Pollution emission	$\hat{e}^{\mathrm{III}} = \dfrac{25}{17}(36 - d)$
Profit	$\hat{\pi}^{\mathrm{III}} = (\hat{q}^{\mathrm{III}})^2 + \hat{t}^{\mathrm{III}}\hat{z}^{\mathrm{III}} - (3/2)(\hat{z}^{\mathrm{III}})^2 + (\hat{z}^{\mathrm{III}})^2$
Social welfare	$\widehat{W}^{\mathrm{III}} = 2(\hat{q}^{\mathrm{III}})^2 + 2\hat{\pi}^{\mathrm{III}} + 2\hat{t}^{\mathrm{III}}\,\hat{e}^{\mathrm{III}} - 2d\hat{e}^{\mathrm{III}}$

Table A2(IV): Extended equilibrium outcome under Scenario IV

	Noncooperative ECSR and ERJV cooperation
ECSR level	$\hat{\theta}^{\mathrm{IV}} = 0$
Environmental R&D effort	$\hat{z}^{\mathrm{IV}} = \dfrac{4}{11}(3d - 25)$
Output	$\hat{q}^{\mathrm{IV}} = \dfrac{4}{11}(100 - d)$
Pollution emission	$\hat{e}^{\mathrm{IV}} = \dfrac{4}{11}(125 - 4d)$
Profit	$\hat{\pi}^{\mathrm{IV}} = (\hat{q}^{\mathrm{IV}})^2 + \hat{t}^{\mathrm{IV}}\hat{z}^{\mathrm{IV}} - (3/2)(\hat{z}^{\mathrm{IV}})^2 + (\hat{z}^{\mathrm{IV}})^2$
Social welfare	$\widehat{W}^{\mathrm{IV}} = 2(\hat{q}^{\mathrm{IV}})^2 + 2\hat{\pi}^{\mathrm{IV}} + 2\hat{t}^{\mathrm{IV}}\,\hat{e}^{\mathrm{IV}} - 2d\hat{e}^{\mathrm{IV}}$

Table A2(V): Extended equilibrium outcome under Scenario V

	Cooperative ECSR and noncooperative environmental R&D
ECSR level	$\hat{\theta}^{\mathrm{V}}=\begin{cases}\hat{\theta}_0^{\mathrm{V}}=\dfrac{100(3-\delta)^2}{d(63-42\delta+4\delta^2)} & if\ \dfrac{50}{3}< d\le\dfrac{200}{7}\\ \hat{\theta}_{\mathrm{P}}^{\mathrm{V}}=\dfrac{100(54-63\delta+18\delta^2-\delta^3)-d(54-99\delta+21\delta^2-\delta^3)}{d(6-\delta)(45-30\delta+2\delta^2)} & if\ \dfrac{200}{7}< d<36\end{cases}$
Environmental R&D effort	$\hat{z}^{\mathrm{V}}=\begin{cases}\hat{z}_0^{\mathrm{V}}=\dfrac{100(3-\delta)}{63-42\delta+4\delta^2} & if\ \dfrac{50}{3}< d\le\dfrac{200}{7}\\ \hat{z}_{\mathrm{P}}^{\mathrm{V}}=\dfrac{3d(6-\delta)-100(3-\delta)}{45-30\delta+2\delta^2} & if\ \dfrac{200}{7}< d<36\end{cases}$
Output	$\hat{q}^{\mathrm{V}}=\begin{cases}\hat{q}_0^{\mathrm{V}}=\dfrac{100(18-12\delta+\delta^2)}{63-42\delta+4\delta^2} & if\ \dfrac{50}{3}< d\le\dfrac{200}{7}\\ \hat{q}_{\mathrm{P}}^{\mathrm{V}}=\dfrac{100(21-13\delta+\delta^2)-d(6-\delta)^2}{45-30\delta+2k\delta^2} & if\ \dfrac{200}{7}< d<36\end{cases}$
Pollution emission	$\hat{e}^{\mathrm{V}}=\begin{cases}\hat{e}_0^{\mathrm{V}}=\dfrac{100(15-11\delta+\delta^2)}{63-42\delta+4\delta^2} & if\ \dfrac{50}{3}< d\le\dfrac{200}{7}\\ \hat{e}_{\mathrm{P}}^{\mathrm{V}}=\dfrac{100(21-13\delta+\delta^2)-d(6-\delta)^2}{45-30\delta+2\delta^2} & if\ \dfrac{200}{7}< d<36\end{cases}$
Profit	$\hat{\pi}^{\mathrm{V}}=\begin{cases}\hat{\pi}_0^{\mathrm{V}}=\dfrac{5000(15-10\delta+\delta^2)}{63-42\delta+4\delta^2} & if\ \dfrac{50}{3}< d\le\dfrac{200}{7}\\ \hat{\pi}_{\mathrm{P}}^{\mathrm{V}}=(\hat{q}_{\mathrm{P}}^{\mathrm{V}})^2+\hat{t}_{\mathrm{P}}^{\mathrm{V}}\,\hat{z}_{\mathrm{P}}^{\mathrm{V}}-(3/2)(\,\hat{z}_{\mathrm{P}}^{\mathrm{V}})^2+\delta(\hat{z}_{\mathrm{P}}^{\mathrm{V}})^2 & if\ \dfrac{200}{7}< d<36\end{cases}$
Social welfare	$\widehat{W}^{\mathrm{V}}=\begin{cases}\widehat{W}_0^{\mathrm{V}}=2(\hat{q}_0^{\mathrm{V}})^2+2\hat{\pi}_0^{\mathrm{V}}-2d\hat{e}_0^{\mathrm{V}} & if\ \dfrac{50}{3}< d\le\dfrac{200}{7}\\ \widehat{W}_{\mathrm{P}}^{\mathrm{V}}=2(\hat{q}_{\mathrm{P}}^{\mathrm{V}})^2+2\hat{\pi}_{\mathrm{P}}^{\mathrm{V}}+2\hat{t}_{\mathrm{P}}^{\mathrm{V}}\hat{e}_{\mathrm{P}}^{\mathrm{V}}-2d\hat{e}_{\mathrm{P}}^{\mathrm{V}} & if\ \dfrac{200}{7}< d<36\end{cases}$

Table A2(VI): Extended equilibrium outcome under Scenario VI

	Cooperative ECSR and cooperative environmental R&D
ECSR level	$\hat{\theta}^{\mathrm{VI}}=\begin{cases}\hat{\theta}_0^{\mathrm{VI}}=\dfrac{25(3-2\delta)}{2d(6-\delta)} & if\ \dfrac{3000}{203}< d\le\dfrac{1475}{58}\\ \hat{\theta}_{\mathrm{P}}^{\mathrm{VI}}=\dfrac{(100-d)(3-2\delta)(87-40\delta+4\delta^2)}{2d(1557-798\delta+140\delta^2-8\delta^3)} & if\ \dfrac{1475}{58}< d<\dfrac{9100}{289}\end{cases}$
Environmental R&D effort	$\hat{z}^{\mathrm{VI}}=\begin{cases}\hat{z}_0^{\mathrm{VI}}=\dfrac{50}{2(6-\delta)} & if\ \dfrac{3000}{203}< d\le\dfrac{1475}{58}\\ \hat{z}_{\mathrm{P}}^{\mathrm{VI}}=\dfrac{d(21-2\delta)(87-40\delta+4\delta^2)-600(15-2\delta)(3-2\delta)}{(3-2\delta)(1557-798\delta+140\delta^2-8\delta^3)} & if\ \dfrac{1475}{58}< d<\dfrac{9100}{289}\end{cases}$
Output	$\hat{q}^{\mathrm{VI}}=\begin{cases}\hat{q}_0^{\mathrm{VI}}=\dfrac{25(15-2\delta)}{2(6-\delta)} & if\ \dfrac{3000}{203}< d\le\dfrac{1475}{58}\\ \hat{q}_{\mathrm{P}}^{\mathrm{VI}}=\dfrac{(100-d)(15-2\delta)(87-40\delta+4\delta^2)}{2(1557-798\delta+140\delta^2-8\delta^3)} & if\ \dfrac{1475}{58}< d<\dfrac{9100}{289}\end{cases}$
Pollution emission	$\hat{e}^{\mathrm{VI}}=\begin{cases}\hat{e}_0^{\mathrm{VI}}=\dfrac{25(13-2\delta)}{2(6-\delta)} & if\ \dfrac{3000}{203}< d\le\dfrac{1475}{58}\\ \hat{e}_{\mathrm{P}}^{\mathrm{VI}}=\dfrac{100(15-2\delta)(11-2\delta)(9-2\delta)(3-2\delta)-d(87-40\delta+4\delta^2)^2}{2(3-2\delta)(1557-798\delta+140\delta^2-8\delta^3)} & if\ \dfrac{1475}{58}< d<\dfrac{9100}{289}\end{cases}$
Profit	$\hat{\pi}^{\mathrm{VI}}=\begin{cases}\hat{\pi}_0^{\mathrm{VI}}=\dfrac{625(11-2\delta)}{6-\delta} & if\ \dfrac{3000}{203}< d\le\dfrac{1475}{58}\\ \hat{\pi}_{\mathrm{P}}^{\mathrm{VI}}=(\hat{q}_{\mathrm{P}}^{\mathrm{VI}})^2+\hat{t}_{\mathrm{P}}^{\mathrm{VI}}\,\hat{z}_{\mathrm{P}}^{\mathrm{VI}}-(3/2)(\hat{z}_{\mathrm{P}}^{\mathrm{VI}})^2+\delta(\hat{z}_{\mathrm{P}}^{\mathrm{VI}})^2 & if\ \dfrac{1475}{58}< d<\dfrac{9100}{289}\end{cases}$
Social welfare	$\widehat{W}^{\mathrm{VI}}=\begin{cases}\widehat{W}_0^{\mathrm{VI}}=2(\hat{q}_0^{\mathrm{VI}})^2+2\hat{\pi}_0^{\mathrm{VI}}-2d\hat{e}_0^{\mathrm{VI}} & if\ \dfrac{3000}{203}< d\le\dfrac{1475}{58}\\ \widehat{W}_{\mathrm{P}}^{\mathrm{VI}}=2(\hat{q}_{\mathrm{P}}^{\mathrm{VI}})^2+2\hat{\pi}_{\mathrm{P}}^{\mathrm{VI}}+2\hat{t}_{\mathrm{P}}^{\mathrm{VI}}\hat{e}_{\mathrm{P}}^{\mathrm{VI}}-2d\hat{e}_{\mathrm{P}}^{\mathrm{VI}} & if\ \dfrac{1475}{58}< d<\dfrac{9100}{289}\end{cases}$

Table A2(VII): Extended equilibrium outcome under Scenario VII

	Cooperative ECSR and ERJV competition
ECSR level	$\hat{\theta}^{\mathrm{VII}} = \begin{cases} \hat{\theta}_0^{\mathrm{VII}} = \dfrac{16}{d} \quad if \ \dfrac{50}{3} < d \leq \dfrac{112}{5} \\ \hat{\theta}_{\mathrm{P}}^{\mathrm{VII}} = \dfrac{5(32+d)}{17d} \quad if \ \dfrac{112}{5} < d < \dfrac{125}{4} \end{cases}$
Environmental R&D effort	$\hat{z}^{\mathrm{VII}} = \begin{cases} \hat{z}_0^{\mathrm{VII}} = 8 \quad if \ \dfrac{50}{3} < d \leq \dfrac{112}{5} \\ \hat{z}_{\mathrm{P}}^{\mathrm{VII}} = \dfrac{5}{17}(3d-40) \quad if \ \dfrac{112}{5} < d < \dfrac{125}{4} \end{cases}$
Output	$\hat{q}^{\mathrm{VII}} = \begin{cases} \hat{q}_0^{\mathrm{VII}} = 28 \quad if \ \dfrac{50}{3} < d \leq \dfrac{112}{5} \\ \hat{q}_{\mathrm{P}}^{\mathrm{VII}} = \dfrac{10}{17}(70-d) \quad if \ \dfrac{112}{5} < d < \dfrac{125}{4} \end{cases}$
Pollution emission	$\hat{e}^{\mathrm{VII}} = \begin{cases} \hat{e}_0^{\mathrm{VII}} = 20 \quad if \ \dfrac{50}{3} < d \leq \dfrac{112}{5} \\ \hat{e}_{\mathrm{P}}^{\mathrm{VII}} = \dfrac{25}{17}(36-d) \quad if \ \dfrac{112}{5} < d < \dfrac{125}{4} \end{cases}$
Profit	$\hat{\pi}^{\mathrm{VII}} = \begin{cases} \hat{\pi}_0^{\mathrm{VII}} = 1200 \quad if \ \dfrac{50}{3} < d \leq \dfrac{112}{5} \\ \hat{\pi}_{\mathrm{P}}^{\mathrm{VII}} = (\hat{q}_{\mathrm{P}}^{\mathrm{VII}})^2 + \hat{t}_{\mathrm{P}}^{\mathrm{VII}}\hat{z}_{\mathrm{P}}^{\mathrm{VII}} - (3/2)(\hat{z}_{\mathrm{P}}^{\mathrm{VII}})^2 + (\hat{z}_{\mathrm{P}}^{\mathrm{VII}})^2 \quad if \ \dfrac{112}{5} < d < \dfrac{125}{4} \end{cases}$
Social welfare	$\widehat{W}^{\mathrm{VII}} = \begin{cases} \widehat{W}_0^{\mathrm{VII}} = 3968 - 40d \quad if \ \dfrac{50}{3} < d \leq \dfrac{112}{5} \\ \widehat{W}_{\mathrm{P}}^{\mathrm{VII}} = 2(\hat{q}_{\mathrm{P}}^{\mathrm{VII}})^2 + 2\hat{\pi}_{\mathrm{P}}^{\mathrm{VII}} + 2\hat{t}_{\mathrm{P}}^{\mathrm{VII}}\hat{e}_{\mathrm{P}}^{\mathrm{VII}} - 2d\hat{e}_{\mathrm{P}}^{\mathrm{VII}} \quad if \ \dfrac{112}{5} < d < \dfrac{125}{4} \end{cases}$

Table A2(VIII): Extended equilibrium outcome under Scenario VIII

	Cooperative ECSR and ERJV cooperation
ECSR level	$\hat{\theta}^{\mathrm{VIII}} = \begin{cases} \hat{\theta}_0^{\mathrm{VIII}} = \dfrac{5}{2d} \quad if \ \dfrac{50}{3} < d \leq \dfrac{215}{17} \\ \hat{\theta}_{\mathrm{P}}^{\mathrm{VIII}} = \dfrac{17(100-d)}{594d} \quad if \ \dfrac{215}{17} < d < \dfrac{125}{4} \end{cases}$
Environmental R&D effort	$\hat{z}^{\mathrm{VIII}} = \begin{cases} \hat{z}_0^{\mathrm{VIII}} = 5 \quad if \ \dfrac{50}{3} < d \leq \dfrac{215}{17} \\ \hat{z}_{\mathrm{P}}^{\mathrm{VIII}} = \dfrac{1}{297}(323d - 2600) \quad if \ \dfrac{215}{17} < d < \dfrac{125}{4} \end{cases}$
Output	$\hat{q}^{\mathrm{VIII}} = \begin{cases} \hat{q}_0^{\mathrm{VIII}} = \dfrac{65}{2} \quad if \ \dfrac{50}{3} < d \leq \dfrac{215}{17} \\ \hat{q}_{\mathrm{P}}^{\mathrm{VIII}} = \dfrac{221}{594}(100-d) \quad if \ \dfrac{215}{17} < d < \dfrac{125}{4} \end{cases}$
Pollution emission	$\hat{e}^{\mathrm{VIII}} = \begin{cases} \hat{e}_0^{\mathrm{VIII}} = \dfrac{55}{2} \quad if \ \dfrac{50}{3} < d \leq \dfrac{215}{17} \\ \hat{e}_{\mathrm{P}}^{\mathrm{VIII}} = \dfrac{1}{198}(9100 - 289d) \quad if \ \dfrac{215}{17} < d < \dfrac{125}{4} \end{cases}$
Profit	$\hat{\pi}^{\mathrm{VIII}} = \begin{cases} \hat{\pi}_0^{\mathrm{VIII}} = 1125 \quad if \ \dfrac{50}{3} < d \leq \dfrac{215}{17} \\ \hat{\pi}_{\mathrm{P}}^{\mathrm{VIII}} = (\hat{q}_{\mathrm{P}}^{\mathrm{VIII}})^2 + \hat{t}_{\mathrm{P}}^{\mathrm{VIII}}\hat{z}_{\mathrm{P}}^{\mathrm{VIII}} - (3/2)(\hat{z}_{\mathrm{P}}^{\mathrm{VIII}})^2 + (\hat{z}_{\mathrm{P}}^{\mathrm{VIII}})^2 \quad if \ \dfrac{215}{17} < d < \dfrac{125}{4} \end{cases}$
Social welfare	$\widehat{W}^{\mathrm{VIII}} = \begin{cases} \widehat{W}_0^{\mathrm{VIII}} = \dfrac{5}{2}(1745 - 22d) \quad if \ \dfrac{50}{3} < d \leq \dfrac{215}{17} \\ \widehat{W}_{\mathrm{P}}^{\mathrm{VIII}} = 2(\hat{q}_{\mathrm{P}}^{\mathrm{VIII}})^2 + 2\hat{\pi}_{\mathrm{P}}^{\mathrm{VIII}} + 2\hat{t}_{\mathrm{P}}^{\mathrm{VIII}}\hat{e}_{\mathrm{P}}^{\mathrm{VIII}} - 2d\hat{e}_{\mathrm{P}}^{\mathrm{VIII}} \quad if \ \dfrac{215}{17} < d < \dfrac{125}{4} \end{cases}$