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Abstract: This study considers strategic relations between emission tax and environmental corporate social responsibility (ECSR) in a Cournot–Bertrand comparison, and analyzes two different timings of the games between a tax-then-ECSR (T game) and an ECSR-then-tax (E game). We show that the T game always yields higher emission tax than the E game irrespective of competition modes, but lower ECSR under Cournot while higher ECSR when the marginal damage is high under Bertrand. Additionally, compared with Bertrand, Cournot yields lower (higher) ECSR in the T (E) game, but lower emission tax in the E game while higher emission tax when the product substitutability is low in the T game. We finally show that firms always prefer Cournot competition with the commitment of E game irrespective of the product substitutability and marginal damage.

Keywords: Emission tax; environmental corporate social responsibility; Cournot–Bertrand comparison; tax-then-ECSR; ECSR-then-tax

JEL Classification: H23; L13; M14

1. Introduction

In recent decades, fulfilling corporate social responsibility (CSR) has become a strategic behavior of companies all over the world. With the increasing awareness of sustainable development, the attention to CSR has been extended to wide concerns on not only consumer's well-being but also the environment, such as environmental corporate social responsibility (ECSR).[1] A large number of companies have established environmental performance goals, participated in greenhouse gas reduction programs, and made voluntary environmental investments to support environmental sustainability, which is regarded as an initiative of ECSR.

At the same time, global concern about environmental degradation and climate change has led many progressive countries to adopt market-based environmental regulatory policies, such as emissions taxes, pollution permits, and abatement subsidies.[2] Under the pressure of government regulations, firms worldwide have carried out environmental research and development projects that aim at improving environmental quality.

In the literature on environmental economics, public concerns on environmental quality and imperfect market structure have been prominent as well.[3] In earlier studies, the analysis of ECSR is mainly based on qualitative research. For instance, Sprinkle and Maines (2010) stated that ECSR can be regarded as an effective lever for easing legal or regulatory constraints and for avoiding possibly stricter policy penalties. Meanwhile, Khojastehpour and Johns (2014) showed that ECSR helps to build firms' public reputation and improve firm's profitability. Recently, the effect of firms' ECSR initiation has been explored using theoretical models. For example, Fukuda and Ouchida (2020) and Wang (2021) investigated the effect of ECSR in a monopoly market and indicated that the promotion of ECSR invariably enhances consumer surplus, profit, and social welfare, while ECSR is not always beneficial for the environment.

[1] KPMG (2017) showed that 78% of the world's top 25 companies undertook corporate responsibility and reported relative data to attract investors; and 67% of them also set interval carbon reduction targets in 2017. For further comprehensive studies on CSR and ECSR, see Bénabou and Tirole (2010), Schreck (2011), Kitzmueller and Shimshack (2012), Crifo and Forget (2015), Hirose et al. (2017, 2020).

[2] For more recent discussion about environmental policies, see Xu and Lee (2018) and García et al. (2018), among others.

[3] Early studies have investigated the effect of environmental taxes in oligopolistic markets. For instance, Shaffer (1995) and Lee (1999) investigated the optimal ad valorem tax and output tax as an effective way of environmental regulation, respectively.

However, recent works have extended the analysis into various cases where the firms might have different objectives. For example, Ohori (2006), Pal and Saha (2014, 2015), and Xu et al. (2016) examined emission tax together with privatization policies in a mixed oligopoly where state-owned firms compete with private firms. Hirose et al. (2017, 2020) and Lee and Park (2019) considered a delegation game with ECSR and analyzed the firms' profitability and the effect of ECSR on environmental quality and social welfare. Some recent studies on environmental problems have also considered the timing of emission taxes and other policies in an oligopoly market.[4] In particular, Lian et al. (2018) investigated the strategic environmental taxes in a free entry oligopoly, while García et al. (2018) and Leal et al. (2018) analyzed the impact of the timing of environmental regulations and a consumer-friendly firm's abatement activity on welfare and environmental quality.

In comparing the strategic relations between emission tax policy and ECSR activities, it is worthwhile to examine the timing of these two strategies in various competition modes.[5] In a Cournot–Bertrand comparison where product differentiation and environmental damage are taken into consideration, we examine the optimal emission tax and strategic ECSR under both price and quantity competition modes in a duopoly market. In particular, we compare two different timings of the games: tax-then-ECSR (named T game) and ECSR-then-tax (named E game). In the former, the government decides the emission tax level and then firms determine the level of ECSR. The latter is a reversed order of the former in which the firm determines the level of ECSR before the government decides the emission tax level. We investigate the impact of the timing of emission tax and ECSR on the firm's profit, environmental quality, and welfare.

Our main findings are as follows. First, we show that the optimal emission tax rate is lower than the marginal damage, and it is higher in the T game than that in the E game, irrespective of the competition mode. However, the relationships concerning ECSR in the T game versus the E game depend on the competition mode. In particular, the T game yields lower ECSR than the E game under

[4] For the impact of different timing, see Poyago-Theotoky and Teerasuwannajak (2002), Xu et al. (2017), and Lee et al. (2018), among others.

[5] Since Singh and Vives (1984), the economic literature has paid attention to comparing Cournot–Bertrand competition modes in a differentiated oligopoly. Further, recent works have also conducted price versus quantity comparisons in a mixed oligopoly. See, for instance, Ghosh and Mitra (2010), Matsumura and Ogawa (2012), Scrimitore (2014), Haraguchi and Matsumura (2014, 2015), Nakamura (2015), Xu et al. (2016), and Buccella et al. (2021).

Cournot competition, while lower (higher) ECSR when the marginal damage is low (high) under Bertrand competition. Furthermore, the T game always yields higher social welfare and lower environmental damage than the E game irrespective of the competition mode. Thus, the government should have a first-mover advantage before the firms choose how to compete in prices or quantities.

Second, the strategic ECSR is lower under Cournot than that under Bertrand in the T game and the opposite result can be obtained in the E game. However, the optimal emission tax is always lower under Cournot than that under Bertrand in the E game, while higher (lower) when product substitutability is low (high) in the T game.[6] Further, the environmental damage is lower (higher) under Cournot than that under Bertrand in the T (E) game. However, social welfare is always lower under Cournot than that under Bertrand irrespective of the timing of emission taxes and ECSR activities. This finding of the welfare ranking is consistent with that in the literature on mixed and private duopoly markets.

Finally, we extend the analysis into the strategic decision of the firms regarding the order of the commitment timing of ECSR (T game versus E game) and competition modes (Cournot competition versus Bertrand competition). We show that irrespective of product substitutability and marginal damage, firms choose Cournot competition then play the E game when the competition mode is determined from the beginning of the game. Moreover, if firms can commit the timing of ECSR before the emission tax, they play the E game and then choose Cournot competition. These findings suggest that Cournot competition with the strategic commitment to ECSR can appear at equilibrium in the relations between the emission tax policy and ECSR activities.

The organization of this study is as follows. Section 2 introduces the basic model. We analyze Cournot and Bertrand competitions in the T game in section 3 and then analyze them in the E game in section 4. In section 5, we compare the main results between Cournot and Bertrand competitions in each game. Section 6 extends the analysis into the strategic decision of firms regarding the order of the timing of ECSR and competition modes. Finally, the concluding remarks are provided.

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[6] Our results are in contrast with those of Xu et al. (2016), who demonstrated that the optimal emission tax is always lower under Cournot competition than that under Bertrand when the emissions taxes and privatization policies are used together.

2. Basic model

We consider a duopoly market in which firms provide differentiated products. Following Dixit (1979), a representative consumer's utility function is

$$U(q_1, q_2) = q_1 + q_2 - \frac{1}{2}({q_1}^2 + 2bq_1q_2 + {q_2}^2), \tag{1}$$

where q_1 and q_2 are the output of two firms, respectively, and $b \in (0, 1)$ measures the degree of product substitutability. A higher value for b represents higher substitutability or lower differentiation. The inverse demand function of the firm is $p_i = 1 - q_i - bq_j,\ i = j = 1, 2,\ i \neq j$, where p_i denotes the price of firm *i*'s product. Then, the consumer surplus is $CS = \frac{1}{2}({q_1}^2 + {q_2}^2 + 2bq_1q_2)$. It is noted that higher substitutability increases the consumer surplus despite reducing consumers' willingness to pay for products.

The production leads to pollution in which q_i units of output cause e_i units of emission. Both firms can reduce emissions by undertaking abatement activities. The abatement technology is an end-of-pipe technology and we assume that the cost function of the abatement is quadratic. In this case, firm *i* sets the pollution abatement level at $a_i \in [0, q_i]$ to reduce emission by investing abatement activities at a cost of a_i^2. Thus, the emission level of firm *i* is $e_i = q_i - a_i$. We assume that the environmental damage function is $ED = d\sum_i e_i$, where $d \in (0, 1)$ denotes marginal environmental damage. Furthermore, the government imposes a regulatory tax t on the emission level, and the environmental tax revenue is given as $T = t\sum_i e_i$.[7]

Finally, the firms' production cost function is symmetric and takes a quadratic form, $C(q_i) = F + q_i^2$, where $F = 0$ without loss of generality. Thus, the profit of firm *i* is

$$\pi_i = p_iq_i - q_i^2 - te_i - a_i^2. \tag{2}$$

Social welfare is the sum of the producer surplus, consumer surplus, and tax revenue, minus environmental damage:

$$W = \sum_i \pi_i + CS + T - ED. \tag{3}$$

Regarding the firms' objective functions, we consider there exists managerial delegation in both firms. The owner maximizes the profits but specifies a concern for environmental damage as an ECSR

[7] Note that we allow for a negative value of the emission tax but assume that $t \leq 1$ in order to support interior solutions in the analysis.

initiative to the manager. Then, the manager maximizes profits plus a fraction of environmental damage in production. This indicates that both firms behave as ECSR firms that do not only seek profit maximization but also have awareness of the environment. Specifically, following Lee and Park (2019) and Hirose et al. (2017, 2020), the manager's objective function is a combination of firm *i*'s profit and the environmental damage:

$$V_i = \pi_i - \beta_i ED, \tag{4}$$

where $\beta_i \in [0, 1]$ represents the degree of ECSR, in which the ECSR incentive is related to environmental damage. Note that $\beta_i = 0$ indicates that firm *i* is a private firm pursuing absolute profits.

We examine two cases of the timings of the games. The first one is a standard case of tax-then-ECSR in which the government decides the emission tax level and then the owners of the firms determine the level of ECSR. The other is a reversed order of the T game, the ECSR-then-tax case, in which the owners of the firms determine the level of ECSR before the government decides the emission tax level. In the final stage, two firms compete in Cournot or Bertrand competition. In the following sections, we discuss the two competition modes in the T and E games, respectively.

3. Tax-then-ECSR: T game

In this section, we examine a tax-then-ECSR case in which a three-stage game is constructed. The government chooses *t* to maximize social welfare in the first stage. Given emission tax rates, the owner of firm *i* chooses β_i to maximize profit in the second stage. Two firms decide the level of abatements and outputs (or prices) simultaneously in the final stage.[8] We solve the subgame perfect Nash equilibrium through backward induction.

3.1 Cournot competition

We first consider the T game under Cournot competition. In the third stage, Cournot firm *i* decides q_i and a_i to maximize V_i in Eq. (4). Then, the first-order conditions are[9]

$$\frac{\partial V_i}{\partial q_i} = 1 - t - 4q_i - bq_j - d\beta_i, \; \frac{\partial V_i}{\partial a_i} = t - 2a_i + d\beta_i. \tag{5}$$

[8] Note that due to the separability property of an end-of-pipe abatement technology, the order of choosing the levels of abatement and output is neutral to the equilibrium outcome in the T game.

[9] To ensure that the equilibrium levels of the output, abatement, and emission are non-negative, we assume that $d_1 \leq d \leq d_2$, where d_i is shown in Appendix.

Eq. (5) yields the following equilibrium outputs and abatements in the third stage:

$$q_i = \frac{(4-b)(1-t)-d(4\beta_i-b\beta_j)}{16-b^2},\ a_i = \frac{t+d\beta_i}{2}. \tag{6}$$

A few remarks are in order. First, both the emission and output of the firm decrease with emission tax, whereas the abatement increases with emission tax; that is, $\partial q_i/\partial t < 0$, $\partial e_i/\partial t < 0$, and $\partial a_i/\partial t > 0$, where $i = j = 1,2$, $i \neq j$. Second, both the output and emission of the firm decrease with its level of ECSR, while both increase with the rival's level of ECSR; that is, $\partial q_i/\partial \beta_i < 0$, $\partial q_i/\partial \beta_j > 0$, $\partial e_i/\partial \beta_i < 0$, and $\partial e_i/\partial \beta_j > 0$. Third, the abatement increases with its level of ECSR, while it is independent of the rival's level of ECSR, that is, $\partial a_i/\partial \beta_i > 0$ and $\partial a_i/\partial \beta_j = 0$. Finally, both the total output and total emission decrease with the level of ECSR, whereas the total abatement increases with the level of ECSR; that is, $\partial(q_i + q_j)/\partial \beta_i < 0$, $\partial(e_i + e_j)/\partial \beta_i < 0$, and $\partial(a_i + a_j)/\partial \beta_i > 0$.

The profit of firm *i* and social welfare are, respectively,

$$\pi_i = \frac{(4-b)^2(8-16t+24t^2+8bt^2+b^2t^2)+H_1 d+H_2 d^2}{4(16-b^2)^2} \text{ and}$$

$$W = \frac{2(4-b)^2 H_3+d(H_4(\beta_1^2-\beta_2^2)d+4b(8-b^2)\beta_1\beta_2 d+2H_5(\beta_1+\beta_2)}{4(16-b^2)^2}, \tag{7}$$

where H_i is provided in Appendix.

In the second stage, firm *i* chooses β_i to maximize its profit in Eq. (7). Then, since $\partial \pi_i/\partial \beta_i < 0$,[10] the strategic level of ECSR is

$$\beta_i^{CT} = 0, \tag{8}$$

where superscript "CT" denotes the equilibrium results in the T game under Cournot competition. Note that no Cournot firms engage in ECSR activities if the government sets the emission tax before the firms. This finding is consistent with that of Hirose et al. (2020), who showed that no firms engage in ECSR activities in a differentiated Cournot duopoly market, even in the absence of emission tax.

In the first stage, the government chooses t to maximize social welfare in Eq. (7). Then, the differentiation of W with respect to t yields[11]

$$t^{CT} = \frac{(4+b)(6+b)d-2}{22+10b+b^2}. \tag{9}$$

Eq. (9) shows that the optimal emission tax is positive and increases with *b*; that is, $0 < t^{CT} < 1$ and

[10] Note that $\partial \pi_i/\partial \beta_i = -d((384-48b^2+b^4)d\beta_j + 2b^2((4-b)(1-t)+bd\beta_i))/2(16-b^2)^2 < 0$.

[11] It can be easily shown that $\partial^2 W/\partial t^2 < 0$ when $t = t^{CT}$.

$\partial t^{CT}/\partial b > 0$. Further, the committed emission tax in Eq. (9) is lower than the marginal damage; that is, $t^{CT} < MED = d$.

Substituting t^{CT} and β_i^{CT} into q_i and a_i, we have the following equilibrium results:

$$q_i^{CT} = \frac{(6+b)(1-d)}{22+10b+b^2},\ a_i^{CT} = \frac{(4+b)(6+b)d-2}{2(22+10b+b^2)}, \text{ and}$$

$$p_i^{CT} = \frac{16+3b+(1+b)(6+b)d}{22+10b+b^2},\ e_i^{CT} = \frac{2(7+b)-(6+b)^2 d}{2(22+10b+b^2)}. \quad (10)$$

From Eq. (10), we show that the levels of outputs, prices, and emissions of the firm decrease with *b*, whereas the abatement increases with *b*; that is, $\partial q_i^{CT}/\partial b < 0$, $\partial p_i^{CT}/\partial b < 0$, $\partial e_i^{CT}/\partial b < 0$, and $\partial a_i^{CT}/\partial b > 0$.

The profit of firm *i* is

$$\pi_i^{CT} = \frac{292+8b(12+b)-4(6+b)(28+5b)d+(6+b)^2(24+8b+b^2)d^2}{4(22+10b+b^2)^2}. \quad (11)$$

Eq. (11) shows that the firm's profit decreases with *b*; that is, $\partial \pi_i^{CT}/\partial b < 0$.

Social welfare and environmental damage are:

$$W^{CT} = \frac{2(7+b)(1-2d)+(6+b)^2 d^2}{2(22+10b+b^2)},\ ED^{CT} = \frac{2(7+b)d-(6+b)^2 d^2}{22+10b+b^2}. \quad (12)$$

Note that both social welfare and environmental damage decrease with *b*; that is, $\partial W^{CT}/\partial b < 0$ and $\partial ED^{CT}/\partial b < 0$.

3.2 Bertrand competition

We then consider the T game under Bertrand competition. In the third stage, Bertrand firm *i* decides p_i and a_i to maximize V_i in Eq. (4), in which the firm's direct demand function is expressed as:

$$q_i = \frac{1-b+bp_j-p_i}{1-b^2}, \text{ where } i,j = 1,2 \text{ and } i \neq j. \quad (13)$$

Then, the equilibrium prices and abatements can be derived as:[12]

$$p_i = \frac{(4+b^2)(3-b^2+(1+b)t)+(1-b)d(b(3-b^2)\beta_j+2(2-b^2)\beta_i)}{16-9b^2+b^4},\ a_i = \frac{t+d\beta_i}{2}. \quad (14)$$

A few remarks are in order. First, both the abatement and price increase with emission tax rates; that is, $\partial p_i/\partial t > 0$ and $\partial a_i/\partial t > 0$ Second, the price increases with the level of ECSR; that is, $\partial p_i/\partial \beta_i > 0$ and $\partial p_i/\partial \beta_j > 0$, where $i,j = 1,2$ and $i \neq j$. Finally, the abatement increases with its level of

[12] To ensure that the equilibrium levels of output, abatement, and emission are non-negative, we assume that $d_3 \leq d \leq d_4$.

ECSR, while it is independent of the rival's level of ECSR; that is, $\partial a_i/\partial \beta_i > 0$ and $\partial a_i/\partial \beta_j = 0$.

In the second stage, the ECSR is obtained as follows:

$$\beta_i = \frac{2(1-b)(3-b^2)b^2(1-t)}{(96-40b-46b^2+17b^3+7b^4-b^5-b^6)d}. \quad (15)$$

Eq. (5) shows that ECSR activities and the emission tax policy are strategically substitutable; that is, $\partial \beta_i/\partial t < 0$.

In the first stage, the optimal emission tax can be derived as[13]

$$t^{BT} = \frac{2(1-b)H_6+dH_7H_8}{H_9}, \quad (16)$$

where superscript "BT" denotes the equilibrium results in the T game under Bertrand competition. From Eq. (16), the optimal emission tax under Bertrand competition can be negative; that is, $t^{BT} \leq 0$ when $d_3 \leq d \leq d_5$, while $0 < t^{BT} < 1$ when $d_5 < d \leq d_4$. In other words, the government provides an emission subsidy when the marginal damage is relatively low.[14] Moreover, the committed emission tax always increases with *b*; that is, $\partial t^{BT}/\partial b \geq 0$. Finally, the emission tax in Eq. (16) is lower than the marginal damage; that is, $t^{BT} < d$.

Substituting Eq. (16) into Eq. (15), we have the strategic ECSR as follows:

$$\beta_i^{BT} = \frac{H_{10}(1-d)}{H_9 d}. \quad (17)$$

From Eq. (17), we show $0 < \beta_i^{BT} < 1$; that is, the firm always engages in ECSR activities if the government chooses the emission tax before the firm under Bertrand competition, which is in contrast with our result under Cournot competition. Furthermore, the strategic ECSR is inverse U-shaped in b; that is, $\frac{\partial \beta_i^{BT}}{\partial b} \gtreqless 0$ when $b \lesseqgtr 0.715$.

Substituting t^{BT} and β_i^{BT} into q_i and a_i, we obtain the following results at equilibrium:

$$q_i^{BT} = \frac{H_{11}(1-d)}{H_9};\ a_i^{BT} = \frac{H_{12}+H_{13}d}{2H_9};\ p_i^{BT} = \frac{H_{14}+H_{15}d}{H_9};\text{ and }e_i^{BT} = \frac{H_{16}-H_7^2 d}{2H_9}. \quad (18)$$

Note that both the price and emission decrease with *b*, whereas the abatement increases with *b*; that is, $\partial p_i^{BT}/\partial b < 0$, $\partial e_i^{BT}/\partial b < 0$, and $\partial a_i^{BT}/\partial b > 0$. However, the firm's output is U-shaped in b; that is, $\frac{\partial q_i^{BT}}{\partial b} \lesseqgtr 0$ when $b \lesseqgtr 0.696$.

[13] It can be easily shown that $\partial^2 W/\partial t^2 < 0$ when $t = t^{BT}$.

[14] Fukuda and Ouchida (2020) stated that a negative emission tax yields both output-increasing and damage-increasing effects; the emission subsidy is reasonable when the former effect dominates the latter one. This relation also depends on the market structure and the form of demand function (see Lee, 1999).

The profit of firm *i* is

$$\pi_i^{BT} = \frac{4H_{17}H_{18} - H_7H_{19}d + H_7^2H_{20}d^2}{4H_9^2}. \quad (19)$$

Eq. (19) shows that the firm's profit decreases with *b*; that is, $\partial\pi_i^{BT}/\partial b < 0$.

Social welfare and environmental damage are:

$$W^{BT} = \frac{H_{16}(1-2d) + H_7^2d^2}{2H_9}, \ ED^{BT} = \frac{H_{16}d - H_7^2d^2}{2H_9}. \quad (20)$$

Note that social welfare and environmental damage decrease with *b*; that is, $\partial W^{BT}/\partial b < 0$ and $\partial ED^{BT}/\partial b < 0$.

3.3 Comparisons in the T game

Comparing the equilibrium results between Cournot and Bertrand competitions in the T game, we summarize three propositions as follows.[15]

Proposition 1: *The strategic ECSR is always lower under Cournot than that under Bertrand in the T game, whereas the committed emission tax is higher (lower) when the product substitutability is low (high).*

Proof: Comparing the committed emission tax and strategic ECSR between Cournot and Bertrand competitions in the T game, we have $\beta_i^{CT} < \beta_i^{BT}$ and $t^{CT} \gtreqless t^{BT}$ when $b \lesseqgtr 0.238$.

Proposition 1 shows that Cournot firms always choose a lower level of ECSR than Bertrand firms when the government commits emission taxes in the first stage. As shown in Hirose et al. (2020), Cournot firms do not engage in ECSR activities since outputs are strategic substitutes, whereas Bertrand firms always engage in ECSR activities since prices are strategic complements wherein the ECSR is a strategic substitute to the emission tax policy. Proposition 1 also demonstrates that the relationships concerning the emission tax under Cournot versus Bertrand competitions depend on product substitutability. In particular, Cournot competition yields higher (lower) committed emission tax than Bertrand when the product substitutability is low (high). Note that this result is different from that of Xu et al. (2016), who demonstrated that Cournot competition always yields lower emission tax than Bertrand when the government can use emission tax as well as privatization policies to control the firms'

[15] Note that we compare the main results in the T game when $d_1 \le d \le d_2$.

social concern. However, in our study where the firms can choose ECSR strategically, product substitutability plays an essential role in determining the relationships concerning the committed emission tax rate between Cournot and Bertrand competitions in the T game.

<u>Proposition 2</u>: *The equilibrium results between Cournot and Bertrand competitions in the T game have the following relationships:*

(i) $q_i^{CT} < q_i^{BT},\ a_i^{CT} < a_i^{BT},\ p_i^{CT} > p_i^{BT},\ e_i^{CT} < e_i^{BT}$;

(ii) $\pi_i^{CT} \lesseqgtr \pi_i^{BT}$ *when* $d \lesseqgtr d_6$.

Proposition 2 states that Bertrand firms yield higher outputs and higher abatements in the T game and as a result, lower prices but higher emissions. These findings are consistent with those of Singh and Vives (1984) in a private market and Xu et al. (2016) in a mixed market where firms have different objectives. However, contrary to the previous studies, Proposition 2 demonstrates that Bertrand competition generates higher (lower) profit to the firm than Cournot when the marginal damage is low (high).[16]

<u>Proposition 3</u>: *Social welfare and environmental damage are lower under Cournot than those under Bertrand in the T game.*

Proof: Comparing social welfare and environmental damage between Cournot and Bertrand competitions in the T game, we have $W^{CT} < W^{BT}$ and $ED^{CT} < ED^{BT}$.

Proposition 3 states that Bertrand competition generates higher social welfare and higher environmental damage in the T game. The welfare result is consistent with that of Singh and Vives (1984) in a private market and Matsumura and Ogawa (2012) in a mixed market in the absence of environmental issues. However, Proposition 3 also indicates that environmental damage is more serious under Bertrand competition in the T game, which is similar to the result of Xu et al. (2016).

[16] In a mixed duopoly where a profit-oriented private firm competes with a welfare-oriented public firm, it is well-known that a Bertrand firm sets higher outputs but has a higher profit (see Ghosh and Mitra, 2010, and Matsumura and Ogawa, 2012). Further, Scrimitore (2014) considered output subsidy, whereas Haraguchi and Matsumura (2015) extended into an oligopoly setting.

4. ECSR-then-tax: E game

In this section, we examine a reversed order of the T game, the ECSR-then-tax case, in which the owner of firm *i* determines the level of ECSR, then the government chooses the emission tax level. A four-stage game is constructed in the E game.[17] The owner of firm *i* determines β_i to maximize the profit in the first stage. Firm *i* decides the optimal abatement levels a_i in the second stage. The government determines *t* to maximize welfare in the third stage. In the final stage, the two firms compete in quantities (or prices) simultaneously.

4.1 Cournot competition

We first consider the E game under Cournot competition. In the fourth stage, Cournot firm *i* decides q_i to maximize V_i in Eq. (4). Solving the first-order conditions yields the following equilibrium output:[18]

$$q_i = \frac{(4-b)(1-t)+bd\beta_j-4d\beta_i}{16-b^2}. \tag{21}$$

The profit of firm *i* and social welfare are, respectively,

$$\pi_i = \frac{a_i\,(t-a_i)(16-b^2)^2+((4-b)(1-t)+bd\beta_j-4d\beta_i)(2(4-b)(1-t)+2bd\beta_j+(8-b^2)d\beta_i)}{(16-b^2)^2},$$

$$W = \frac{H_{21}+2\left(16-b^2\right)^2\left((d-a_1)a_1+(d-a_2)a_2\right)+d(H_{22}+\beta_2 H_{23})}{2(16-b^2)^2}. \tag{22}$$

In the third stage, the differentiation of *W* in Eq. (22) with respect to t yields

$$t = \frac{2(4+b)d-(3+b)d(\beta_1+\beta_2)-2}{2(3+b)}. \tag{23}$$

Note that the emission tax policy and ECSR activities are strategically substitutable; that is, $\partial t/\partial\beta_i < 0$, where $i = j = 1{,}2,\ i \neq j$.

In the second stage, the differentiation of V_i with respect to a_i yields

$$a_i = \frac{2(4+b)d+(3+b)(\beta_i-\beta_j)d-2}{4(3+b)}. \tag{24}$$

In the first stage, assuming an interior solution, the differentiation of π_i in Eq. (22) with respect to β_i

[17] One may consider the other order of the game where the firm chooses abatement levels a_i in the third stage after the government chooses *t* in the second stage. In this case, the equilibrium outcomes are close to the T game because the emission tax directly affects the abatement activities while there exists a strategic relation between the emission tax and ECSR level only. In this analysis, we focus on the strategic effect of the emissions taxes on the abatement activities, which are the resulting outcomes from the ECSR and emission tax in a non-committed regulatory framework.

[18] To ensure that the equilibrium levels of output, abatement, and emission are non-negative, we assume that $d_7 \leq d \leq d_8$.

yields[19]

$$\beta_i^{CE} = \frac{12-24d+b(4d+bd-5)}{(6-b)(3+b)d}, \tag{25}$$

where superscript "CE" denotes the equilibrium results in the E game under Cournot competition. Note that the equilibrium with an interior solution of ECSR depends on marginal damage. That is, we have $0 < \beta_i^{CE} < 1$ only when $d_9 < d < d_{10}$. Otherwise, we have $\beta_i^{CE} = 1$ when $d_7 \leq d \leq d_9$, while $\beta_i^{CE} = 0$ when $d_{10} \leq d \leq d_8$. Thus, no firms engage in ECSR activities when the marginal damage is high. Furthermore, the strategic ECSR decreases with b; that is, $\partial\beta_i^{CE}/\partial b \leq 0$.

Substituting Eq. (25) into Eq. (23), we have the non-committed emission tax as follows:

$$t^{CE} = \frac{48d+2b(3-d-bd)-18}{(6-b)(3+b)}. \tag{26}$$

Eq. (26) shows that $t^{CE} \leq 0$ when $d_7 \leq d \leq d_{11}$ and $t^{CE} > 0$ when $d_{11} < d \leq d_8$. Further, the non-committed emission tax increases with b; that is, $\partial t^{CE}/\partial b \geq 0$. Finally, the non-committed emission tax in Eq. (26) is lower than the marginal damage; that is, $t^{CE} < d$.

Substituting t^{CE} and β_i^{CE} into q_i and a_i, we derive the following equilibrium results:

$$q_i^{CE} = \frac{1-d}{3+b},\ a_i^{CE} = \frac{(4+b)d-1}{2(3+b)},\ p_i^{CE} = \frac{2+d+bd}{3+b}, \text{ and } e_i^{CE} = \frac{3-(6+b)d}{2(3+b)}. \tag{27}$$

Note that the levels of outputs, prices, and emissions decrease with b, whereas the abatement increases with b; that is, $\partial q_i^{CE}/\partial b < 0$, $\partial p_i^{CE}/\partial b < 0$, $\partial e_i^{CE}/\partial b < 0$, and $\partial a_i^{CE}/\partial b > 0$.

The profit of firm i is

$$\pi_i^{CE} = \frac{3(42-13b)-18(24-4b-b^2)d-(432+24b-22b^2-3b^3)d^2}{4(6-b)(3+b)^2}. \tag{28}$$

From Eq. (28), we show that the firm's profit decreases with b; that is, $\partial\pi_i^{CE}/\partial b < 0$.

Social welfare and environmental damage under Cournot are

$$W^{CE} = \frac{(5+2b)(1-2d)+(14+8b+b^2)d^2}{2(3+b)^2}, \text{ and } ED^{CE} = \frac{d(3-6d-bd)}{3+b}. \tag{29}$$

Note that both of them decrease with b; that is, $\partial W^{CE}/\partial b < 0$ and $\partial ED^{CE}/\partial b < 0$.

4.2 Bertrand competition

We then consider the E game under Bertrand competition. In the fourth stage under Bertrand

[19] It can be easily shown that $\partial^2\pi_i/\partial\beta_i^2 < 0$ when $\beta_i = \beta_i^{CE}$, where $i = 1,2$.

competition, the equilibrium level of prices can be derived as:[20]

$$p_i = \frac{(4-b-b^2)(3-b^2+t+bt)+d(1-b)(b(3-b^2)\beta_j+2(2-b^2)\beta_i)}{16-9b^2+b^4}. \tag{30}$$

In the third stage, the emission tax can be derived as:

$$t = \frac{2(4d+b(b+d-bd)-1)-(1-b)(3+b)d(\beta_1+\beta_2)}{2(3+b)}. \tag{31}$$

Note that $\partial t/\partial \beta_i < 0$, where $i, j = 1,2$ and $i \neq j$; that is, the emission tax policy and ECSR activities are strategically substitutable.

In the second stage, the equilibrium levels of abatements can be derived as:

$$a_i = \frac{2(4d+b(b+d-bd)-1)+d(3+b)((1+b)\beta_i-(1-b)\beta_j)}{4(3+b)}. \tag{32}$$

In the first stage, assuming an interior solution, the strategic ECSR is[21]

$$\beta_i^{BE} = \frac{12-17b+6b^3-b^5-(1-b)(24-4b-9b^2+b^4)d}{(2-b)(1+b)(3+b)(3-b^2)d}, \tag{33}$$

where superscript "BE" denotes the equilibrium results in the E game under Bertrand competition. Note that the equilibrium with an interior solution of ECSR depends on marginal damage; that is, we have $0 < \beta_i^{BE} < 1$ when $d_{14} < d < d_{15}$. Otherwise, we have $\beta_i^{BE} = 1$ when $d_{12} \le d \le d_{14}$, while $\beta_i^{BE} = 0$ when $d_{15} \le d \le d_{13}$. Note also that the strategic ECSR decreases with b; that is, $\partial \beta_i^{BE}/\partial b \le 0$.

Substituting Eq. (33) into Eq. (31), we have the following optimal emission tax:

$$t^{BE} = \frac{-2(1-b)(9-4b-b^2)+2(24-17b+b^3)d}{(2-b)(1+b)(3+b)(3-b^2)}. \tag{34}$$

Eq. (34) shows that $t^{BE} \le 0$ when $d_{12} \le d \le d_{16}$ and $0 < t^{BE} < 1$ when $d_{16} < d \le d_{13}$. Furthermore, the emission tax increases with *b*; that is, $\partial t^{BE}/\partial b \ge 0$. Finally, the emission tax in Eq. (34) is lower than the marginal damage; that is, $t^{BE} < d$.

Substituting t^{BE} and β_i^{BE} into q_i and a_i, we derive the following equilibrium results:

$$q_i^{BE} = \frac{1-d}{3+b},\ a_i^{BE} = \frac{24d+b\left(9-6b+4b^2-b^4-(3-b)(2-b+2b^2+b^3)-6\right.}{2(2-b)(1+b)(3+b)(3-b^2)}, \text{ and}$$

$$p_i^{BE} = \frac{2+d+bd}{3+b},\ e_i^{BE} = \frac{18-36d+b(-3+b(-4-6b+2b^2+b^3+(5+9b-b^2(1+b))d))}{2(2-b)(1+b)(3+b)(3-b^2)}. \tag{35}$$

Note that the output, price, and emission decrease with *b*, whereas the abatement increases with *b*; that

[20] To ensure that the equilibrium levels of output, abatement, and emission are non-negative, we assume that $d_{12} \le d \le d_{13}$.
[21] It can be easily shown that $\partial^2 \pi_i/\partial \beta_i^2 < 0$ when $\beta_i = \beta_i^{BE}$, where $i = 1,2$.

is, $\partial q_i^{BE}/\partial b < 0$, $\partial p_i^{BE}/\partial b < 0$, $\partial e_i^{BE}/\partial b < 0$, and $\partial a_i^{BE}/\partial b > 0$.

The profit of firm *i* is

$$\pi_i^{BE} = \frac{H_{24}+H_{25}d+H_{26}d^2}{4(2-b)(1+b)^2(3+b)^2(3-b^2)^2}. \tag{36}$$

From Eq. (36), we show that the firm's profit decreases with b; that is, $\partial \pi_i^{BE}/\partial b < 0$.

Social welfare and environmental damage under Bertrand are

$$W^{BE} = \frac{H_{27}+H_{28}d+H_{29}d^2}{2(2-b)^2(1+b)^2(3+b)^2(3-b^2)^2}, \text{ and}$$

$$ED^{BE} = \frac{(18-3b-4b^2-6b^3+2b^4+b^5)d+(-36+5b^2+9b^3-b^4(1+b))d^2}{(2-b)(1+b)(3+b)(3-b^2)} \tag{37}$$

Note that the environmental damage always decreases with b; that is, $\partial ED^{BE}/\partial b < 0$. Note also that social welfare is inverse U-shaped in b; that is, $\frac{\partial W^{BE}}{\partial b} \gtrless 0$ when $b \lesseqgtr b_1$, where b_1 is shown in Appendix.

4.3 Comparisons in the E game

Comparing the equilibrium results between Cournot and Bertrand competitions in the E game, we summarize three propositions as follows.[22]

<u>**Proposition 4**</u>: *The non-committed emission tax is lower whereas strategic ECSR is higher under Cournot than those under Bertrand in the E game.*

Proof: Comparing the non-committed emission tax and strategic ECSR between Cournot and Bertrand competitions in the E game, we have $t^{CE} < t^{BE}$ and $\beta_i^{CE} \geq \beta_i^{BE}$; the equality holds only when $d \leq d_{14}$.

Proposition 4 implies that irrespective of product substitutability and marginal damage, if the firm determines the ECSR before the government chooses the emission tax, Bertrand competition always yields lower strategic ECSR and higher non-committed emission tax, which is different from the result in the T game (Proposition 1). This is because outputs are strategic substitutes to the Cournot firms; thus, they have higher incentives to adopt ECSR and then, reduce the emission tax if they choose ECSR before the government sets an emission tax. (Note that emission tax is a strategic substitute to the ECSR.)

[22] Note that we compare the main results in the E game when $d_7 \leq d \leq d_8$.

However, Bertrand firms can induce higher tax by committing lower ECSR, which can increase the prices, which are strategic complements to both firms.

Proposition 5: *The equilibrium results between Cournot and Bertrand competitions in the E game have the following relationships:*

(i) $q_i^{CE} = q_i^{BE}$, $a_i^{CE} < a_i^{BE}$, $p_i^{CE} = p_i^{BE}, e_i^{CE} > e_i^{BE}$;

(ii) $\pi_i^{CE} > \pi_i^{BE}$.

Proposition 5 states that irrespective of marginal damage and product substitutability, Bertrand competition generates higher abatements but lower emissions than Cournot competition in the E game, whereas the levels of outputs and prices are the same in the two competition modes. This finding is similar to the previous result in the literature that if both firms have the same cost, the quantities and prices of firms are the same under both Cournot and Bertrand competitions if there are optimal output subsidy policies.[23] However, in the absence of emission, Bertrand always yields lower profits to the firm, which is consistent with the finding in Singh and Vives (1984). Thus, firms prefer Cournot competition in the E game, which is independent of product substitutability and marginal damage.

Proposition 6: *Social welfare is lower whereas environmental damage is higher under Cournot than those under Bertrand in the E game.*

Proof: Comparing social welfare and environmental damage between Cournot and Bertrand competitions in the E game, we have $W^{CE} < W^{BE}$ and $ED^{CE} > ED^{BE}$.

Proposition 6 shows that Bertrand competition generates higher social welfare and lower environmental damage than Cournot competition in the E game. This is contrary to the findings in the T game (Proposition 3) and also in contrast to those of Xu et al. (2016). Therefore, when the government chooses the emission tax before the firms determine the level of ECSR, it prefers Bertrand competition to reduce environmental damage and enhance social welfare.

[23] Regarding the efficiency properties of the output subsidies, Kim and Lee (1995) analyzed the different oligopolistic incentives under asymmetric information and showed that output subsidies can still obtain the first-best allocation.

5. Cournot versus Bertrand

In this section, we proceed to compare the equilibrium outcomes under Cournot versus Bertrand competitions wherein the firms can choose either the T or E game in a subsequent choice stage.

5.1 Comparisons under Cournot competition

We first compare the main results between the T and E games under Cournot competition.[24]

Proposition 7: *The T game always yields higher emission tax and lower ECSR than the E game under Cournot competition.*

Proof: Comparing the optimal emission tax and strategic ECSR in the two cases under Cournot competition, we have $t^{CT} > t^{CE}$ and $\beta_i^{CT} < \beta_i^{CE}$.

Proposition 7 states that when the government commits the emission tax level before the firm determines the level of ECSR, it intends to choose a higher emission tax to induce the firm to reduce emission subsequently in the T game, because both firms do not adopt ECSR. However, if the firm commits the level of ECSR before the government chooses the emission tax level, it will choose a higher ECSR to induce the government to impose a lower emission tax subsequently in the E game. This arises because the emission tax policy and ECSR activities are strategic substitutes under Cournot, irrespective of product substitutability and marginal damage.

Proposition 8: *Comparing the equilibrium results under Cournot competitions yields the following relationships:*

(i) $q_i^{CT} < q_i^{CE}$, $a_i^{CT} > a_i^{CE}$, $p_i^{CT} > p_i^{CE}$, $e_i^{CT} < e_i^{CE}$;

(ii) $\pi_i^{CT} < \pi_i^{CE}$.

Proposition 8 implies that the T game always yields lower output, lower emission, and lower profit under Cournot competition irrespective of the marginal damage and product substitutability. If the government moves before the firm, it chooses a higher emission tax in the first stage, which induces an output-decreasing effect on the firm. Thus, the total output is lower and the market price is higher in the T game. Furthermore, a higher committed emission tax in the T game leads to higher abatement and

[24] Note that we compare the main results under Cournot competition when $d_7 \leq d \leq d_2$.

thus, lower emission. Finally, both firms earn lower profits in the T game; then, they are worse off when the government moves first. In other words, the firm prefers to move before the government to obtain higher profits under Cournot competition.

Proposition 9: *The T game yields higher social welfare and lower environmental damage than the E game under Cournot competition.*

Proof: Comparing social welfare and the environmental damage in the two cases under Cournot competition, we have $W^{CT} > W^{CE}$ and $ED^{CT} < ED^{CE}$.

Proposition 9 demonstrates that the environmental damage is lower and social welfare is higher in the T game, irrespective of the marginal damage and product substitutability. As shown in Proposition 8, firms choose lower total emissions in the T game, which leads to lower environmental damage and further, even though the T game yields lower profits to the firm and lower consumer surplus, it leads to higher social welfare because of the lower environmental damage. Thus, the government prefers to move before the firm to reduce environmental pollution and improve social welfare under Cournot competition.

Combining the results in Propositions 8 and 9, we conclude that the firm prefers the E game in which it commits to ECSR before the government chooses emission tax and then, has a first-mover advantage under Cournot competition. In this case, the firm intends to commit a higher level of ECSR to induce the government to set a lower emission tax rate, which yields more outputs and more emissions. As a result, Cournot competition generates higher environmental damage as well as lower social welfare under the E game. Therefore, there exists a trade-off between the private incentive of the firms and the public incentive of the society.

5.2 Comparisons under Bertrand competition

We then compare the main results between the T and E games under Bertrand competition.[25]

Proposition 10: *The T game always yields higher emission tax than the E game under Bertrand competition, while lower (higher) strategic ECSR when the marginal damage is low (high).*

[25] Note that we compare the main results under Bertrand competition when $d_{12} \leq d \leq d_4$.

Proof: Comparing the strategic ECSR and optimal emission tax between the T and E games under Bertrand, we have $t^{BT} > t^{BE}$ and $\beta_i^{BT} \lesseqgtr \beta_i^{BE}$ when $d \lesseqgtr d_{17}$, respectively.

Proposition 10 shows that when the government commits the emission tax level before the firm determines the level of ECSR under Bertrand competition, it will choose a higher emission tax in the first stage, which is consistent with the result under Cournot competition. This indicates that irrespective of the competition mode, the government always chooses a higher emission tax when it moves before firms. However, the strategic ECSR between the T and E games depends on marginal damage under Bertrand competition. Contrary to Cournot firms, the strategic ECSR in the T game is lower (higher) than that in the E game when the marginal damage is low (high). This arises because the emission tax policy and ECSR activities are strategic substitutes; thus, Bertrand firms choose a higher level of ECSR to induce lower tax when the marginal damage is high.

Proposition 11: *Comparing the equilibrium results under Bertrand competition yields the following relationships:*

(i) $q_i^{BT} < q_i^{BE},\ a_i^{BT} > a_i^{BE},\ p_i^{BT} > p_i^{BE},\ e_i^{BT} < e_i^{BE}$;

(ii) $\pi_i^{BT} \lesseqgtr \pi_i^{BE}$ *when* $d \lesseqgtr d_{18}$.

Proposition 11 states that the T game always yields lower output, higher abatement, higher price, and lower emission under Bertrand competition, which is consistent with those under Cournot competition (Proposition 8). However, Proposition 11 also shows that the profit comparisons between the T and E games under Bertrand competition depend on marginal damage. In particular, when the marginal damage is high, firms earn more profits if it determines ECSR after the government, which is in contrast to the results under Cournot competition. Therefore, when firms compete in prices, they prefer to move before the government when the marginal damage is low, while moving after the government when the marginal damage is high.

Proposition 12: *The T game always yields higher social welfare and lower environmental damage than the E game under Bertrand competition.*

Proof: Comparing social welfare and environmental damage in the two cases under Bertrand competition, we have $W^{BT} > W^{BE}$ and $ED^{BT} < ED^{BE}$, respectively.

Proposition 12 demonstrates that irrespective of the marginal damage and product substitutability, the environmental damage is lower and social welfare is higher in the T game, which is consistent with the results under Cournot competition (Proposition 9). Therefore, the government always prefers to move before the firm to reduce environmental pollution and improve social welfare, irrespective of the competition mode.

Combining the results in Propositions 11 and 12, we conclude that the firm prefers the E (T) game and chooses lower (higher) ECSR when the marginal damage is low (high) under Bertrand competition. In this case, the government always sets a lower level of emission tax in the E game, which yields more outputs and more emissions. As a result, Bertrand competition generates higher environmental damages and lower social welfare in the E game. Therefore, both the firm and the government prefer the T game only when the marginal damage is low. Otherwise, there also exists a trade-off between the private incentive of the firms and the public incentive of the society.

6. Discussion on the order of the firms' choices

In this section, we extend our analysis into the strategic order of the firms' choices between competition modes and the commitment timing of ECSR. On the one hand, we consider a case where both firms choose the competition mode (Cournot or Bertrand) from the beginning of the super-game and then, given the competition mode, both firms determine the timing of ECSR—whether they commit ECSR before the government announces emission taxes (E game) or wait until the government determines the emission tax (T game). On the other hand, we also consider a reversed order where firms choose the competition mode (price or quantity) after they determine the timing of ECSR. We examine these two different orders and provide some policy implications as follows.

6.1 Strategic choice between Cournot and Bertrand

We first consider a case where firms choose the competition mode (price or quantity) before determining the timing of ECSR (T or E game). In this case, we can compare the equilibrium results between Cournot and Bertrand competitions wherein firm *i* can choose either the T or E game in a subsequent choice of competition modes.

From the previous analysis, we can directly compare the subsequent equilibrium outcomes between Cournot and Bertrand competitions. Proposition 8 shows that both firms always prefer the E game under Cournot competition, and Proposition 11 shows that both firms prefer the E (T) game and choose lower (higher) ECSR only when the marginal damage is low (high) under Bertrand competition; that is, $\pi_i^{CT} < \pi_i^{CE}$ and $\pi_i^{BT} \lesseqgtr \pi_i^{BE}$ when $d \lesseqgtr d_{18}$. Thus, we can compare subsequent equilibrium outcomes between Cournot and Bertrand competitions in the two regions.

First, when the marginal damage is low, both firms prefer the E game irrespective of the competition mode. Then, we compare the firm's profit under Cournot and Bertrand competitions in the E game. Proposition 5 shows that $\pi_i^{CE} > \pi_i^{BE}$. Therefore, when the marginal damage is low, both firms choose Cournot competition and then, play the E game where the firm commits the level of ECSR before the government chooses the emission tax level.

Second, when the marginal damage is high, Cournot firms prefer the E game while Bertrand firms prefer the T game. Then, comparing the profits in the two cases, we show that $\pi_i^{CE} > \pi_i^{BT}$. Therefore, when the marginal damage is high, both firms choose Cournot competition and then play the E game where the firm commits the level of ECSR before the government chooses the emission tax level. Thus, we have the following proposition.

Proposition 13: *When firms choose the competition mode—Cournot or Bertrand—before determining the timing of ECSR between the T and E games, they will choose Cournot competition and then play the E game, which is independent of the product substitutability and marginal damage.*

This finding suggests that regarding competition modes, Cournot competition followed by playing can appear at equilibrium in the relations between the emission tax policy and ECSR activities.

6.2 Strategic commitment to ECSR

We then consider a reverse case: whether the firm commits to ECSR from the beginning of the super-game before they choose the competition mode—Cournot or Bertrand—in the next period.

First, if both firms choose to commit to ECSR, Proposition 5 shows that $\pi_i^{CE} > \pi_i^{BE}$. Therefore, both firms commit to the E game and then choose Cournot competition. Second, if both firms prefer not to commit before they choose the competition mode, Proposition 2 shows that $\pi_i^{CT} \lesseqgtr \pi_i^{BT}$ when $d \lesseqgtr d_6$. Thus, when the marginal damage is low, T game players prefer Bertrand competition and E game players prefer Cournot competition. However, when the marginal damage is high, firms play the E game and then, choose Cournot competition as a result of $\pi_i^{CE} > \pi_i^{CT}$. Comparing the profits in the two cases, we show that $\pi_i^{CE} > \pi_i^{BT}$. Therefore, firms also play the E game and then, choose Cournot competition when the marginal damage is low. Thus, we have the following proposition.

Proposition 14: *When firms choose the timing of ECSR between the T and E games before determining the competition mode—Cournot or Bertrand—they play the E game and then, choose Cournot competition, which is independent of the product substitutability and marginal damage.*

This finding suggests that regarding the timing of ECSR, Cournot competition under the strategic commitment to ECSR can appear at equilibrium in the relations between the emission tax policy and the ECSR activities.

7. Conclusions

This study considered two different timings of emission tax policy and ECSR activities in a Cournot–Bertrand comparison, and investigated the effects of product substitutability and marginal damage in choosing the optimal emission tax and strategic ECSR. The main findings of this study are as follows. First, irrespective of competition modes, the T game always yields higher emission tax than the E game; but it yields lower ECSR under Cournot competition, while lower (higher) ECSR when the marginal damage is low (high) under Bertrand competition. We also show that the T game generates lower environmental damage and higher social welfare than the E game. Second, we find that Cournot competition yields lower (higher) strategic ECSR than Bertrand competition in the T (E) game, but it yields lower emission taxes in the E game, while higher (lower) emission tax when the product substitutability is low (high) in the T game. We also find that the Cournot competition always yields lower environmental damage than Bertrand in the T game, while the opposite result can be obtained in the E game. However, Cournot competition always yields lower social welfare than Bertrand competition, which is independent of the timing of the game. Finally, irrespective of product substitutability and marginal damage, firms choose Cournot competition and then, play the E game when they choose the competition mode from the beginning of the game. However, if both firms can commit to the strategic ECSR, they choose the E game and then compete in Cournot competition. These findings suggest that Cournot competition with the strategic commitment to ECSR can appear at equilibrium in the relations between emission tax policy and ECSR activities.

Future research is recommended as follows. First, we assumed linear demand and environmental damage functions as well as quadratic production and abatement cost functions. The robustness of the results under general functional forms is remained to be examined. Second, diverse objectives and asymmetric costs of firms should be further considered; it would be interesting to investigate the ECSR initiation of a consumer-friendly. Extending our analysis to a more general model may offer wider scope for future research.

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Appendix: The value of d_i, b_i, and H_i

$d_1 = \frac{2}{(4+b)(6+b)}$, $d_2 = \frac{2(7+b)}{(6+b)^2}$,

$d_3 = \frac{2(1-b)(24-16b-3b^2+4b^3-b^4)(24+8b-19b^2-5b^3+3b^4+b^5)}{(96-40b-52b^2+23b^3+9b^4-3b^5-b^6)(144-72b-58b^2+31b^3+7b^4-3b^5-b^6)}$,

$d_4 = \frac{2(24-16b-3b^2+4b^3-b^4)(168-88b-85b^2+45b^3+15b^4-5b^5-2b^6)}{(144-72b-58b^2+31b^3+7b^4-3b^5-b^6)^2}$,

$d_5 = \frac{2(1-b)(576-192b-224b^2+40b^3-101b^4+72b^5+53b^6-26b^7-9b^8+2b^9+b^{10})}{(144-72b-58b^2+31b^3+7b^4-3b^5-b^6)(96-40b-46b^2+17b^3+7b^4-b^5-b^6)}$,

d_6 satisfies $((b+6)^2(24+8b+b^2)H_9^2 - (22+10b+b^2)^2H_7^2H_{20})d^2 + ((22+10b+b^2)^2H_{17}H_{19} - (672+232b+20b^2)H_9^2)d + (292+96b+8b^2)H_9^2 - 4(22+10b+b^2)^2H_{17}H_8 = 0$,

$d_7 = \frac{1}{4+b}$, $d_8 = \frac{3}{6+b}$, $d_9 = \frac{12-5b}{42-b-2b^2}$, $d_{10} = \frac{12-5b}{24-4b-b^2}$,

$d_{11} = \frac{3(3-b)}{24-b-b^2}$, $d_{12} = \frac{6-9b+6b^2-4b^3+b^5}{24-6b+5b^2-7b^3-b^4+b^5}$, $d_{13} = \frac{18-3b-4b^2-6b^3+2b^4+b^5}{36-5b^2-9b^3+b^4+b^5}$,

$d_{14} = \frac{12-17b+6b^3-b^5}{42-13b-17b^2+b^3+3b^4}$, $d_{15} = \frac{12-b(1+b)(5-b^2)}{24+b(b^3-9b-4)}$, $d_{16} = \frac{(1-b)(9-4b-b^2)}{24-17b+b^3}$,

$$d_{17} = \frac{152064-196992b-134208b^2+235744b^3+49424b^4-126214b^5-12822b^6+41185b^7+3481b^8-9084b^9-864b^{10}+1330b^{11}+158b^{12}-118b^{13}-18b^{14}+5b^{15}+b^{16}}{304128-317952b-307008b^2+384704b^3+134072b^4-204600b^5-38520b^6+64328b^7+9545b^8-13220b^9-2020b^{10}+1748b^{11}+310b^{12}-132b^{13}-28b^{14}+4b^{15}+b^{16}}.$$

d_{18} satisfies $(H_{27}H_9^2 - (2-b)H_7^2H_{20}H_{24}^2)d^2 + (H_{26}H_9^2 + (2-b)H_{24}^2)d + H_{25}H_9^2 - 4(2-b)H_{17}H_{18}H_{24}^2 = 0$,

b_1 satisfies
$$\begin{gathered}864 - 5616b + 6102b^2 + 135b^3 - 2412b^4 + 1449b^5 - 1920b^6 + 878b^7 + 804b^8 \\ -502b^9 - 118b^{10} + 75b^{11} + 8b^{12} - 3b^{13} + (-3024 + 18576b - 22410b^2 + 2583b^3 \\ +11868b^4 - 11835b^5 + 4272b^6 + 2434b^7 - 2244b^8 + 70b^9 + 282b^{10} - 57b^{11} - 8 \\ b^{12} + 5b^{13})d + (2160 - 15552b + 23436b^2 - 2502b^3 - 18381b^4 + 11241b^5 \\ +1774b^6 - 3142b^7 + 612b^8 + 216b^9 - 138b^{10} + 12b^{11} + 9b^{12} - b^{13})d^2 = 0\end{gathered},$$

$H_1 = 4(4-b)b(1-t)(4\beta_2 - b\beta_1)$,

$H_2 = 8b^2\beta_2^2 - 4b^3\beta_1\beta_2 - (384 - 48b^2 + b^4)\beta_1^2$,

$H_3 = 10 + 2b - 4t - (b^2 + 10b + 22)t^2 + d((2b^2 + 20b + 48)t - 4b - 16)$,

$H_4 = 352 - 42b^2 + b^4$,

$H_5 = (4-b)^2\big((b^2 + 10b + 24)d - (b^2 + 10b + 22)t - 2\big)$,

$H_6 = 192b + 224b^2 - 40b^3 + 101b^4 - 72b^5 - 53b^6 + 26b^7 + 9b^8 - 2b^9 - b^{10} - 576$,

$H_7 = 144 - 72b - 58b^2 + 31b^3 + 7b^4 - 3b^5 - b^6$,

$H_8 = 96 - 40b - 46b^2 + 17b^3 + 7b^4 - b^5 - b^6$,

$H_9 = 12672 - 11136b - 9248b^2 + 10528b^3 + 2166b^4 - 3974b^5 - 211b^6 + 802b^7 + 37b^8 - 98b^9 - 9b^{10} + 6b^{11} + b^{12}$,

$H_{10} = 864b^2 - 1296b^3 - 204b^4 + 966b^5 - 172b^6 - 238b^7 + 60b^8 + 26b^9 - 4b^{10} - 2b^{11}$,

$H_{11} = 3456 - 4032b - 672b^2 + 2464b^3 - 586b^4 - 437b^5 + 185b^6 + 22b^7 - 16b^8 - b^9 + b^{10}$,

$H_{12} = -1152 + 1536b + 928b^2 - 1824b^3 + 78b^4 + 620b^5 - 134b^6 - 80b^7 + 26b^8 + 4b^9 - 2b^{10}$,

$H_{13} = 13824 - 12672b - 10176b^2 + 12352b^3 + 2088b^4 - 4594b^5 - 77b^6 + 882b^7 + 11b^8 - 102b^9 - 7b^{10} + 6b^{11} + b^{12}$,

$H_{14} = 9216 - 10560b - 4544b^2 + 8736b^3 + 288b^4 - 2951b^5 + 41b^6 + 595b^7 + 31b^8 - 81b^9 - 9b^{10} + 5b^{11} + b^{12}$,

$H_{15} = 3456 - 576b - 4704b^2 + 1792b^3 + 1878b^4 - 1023b^5 - 252b^6 + 207b^7 + 6b^8 - 17b^9 + b^{11}$,

$H_{16} = 8064 - 9600b - 2272b^2 + 6752b^3 - 1250b^4 - 1494b^5 + 504b^6 + 124b^7 - 58b^8 - 6b^9 + 4b^{10}$,

$H_{17} = -24 + 16b + 3b^2 - 4b^3 + b^4$,

$H_{18} = -1009152 + 1686528b + 380736b^2 - 1957760b^3 + 394296b^4 + 920112b^5 - 288409b^6 - 257142b^7 + 72449b^8 + 57830b^9 - 8847b^{10} - 10770b^{11} + 344b^{12} + 1374b^{13} + 103b^{14} - 112b^{15} - 17b^{16} + 4b^{17} + b^{18}$,

$H_{19} = 387072 - 705024b + 28800b^2 + 627776b^3 - 278144b^4 - 169080b^5 + 119146b^6 + 9687b^7 - 14934b^8 + 1157b^9 - 380b^{10} - 250b^{11} + 276b^{12} + 98b^{13} - 46b^{14} - 13b^{15} + 2b^{16} + b^{17}$,

$H_{20} = 13824 - 13824b - 8064b^2 + 10784b^3 + 1360b^4 - 2964b^5 - 347b^6 + 458b^7 + 119b^8 - 56b^9 - 13b^{10} + 2b^{11} + b^{12}$,

$H_{21} = 2(4-b)^2(1-t)(5+b-8d-2bd+(3+b)t)$,

$H_{22} = \beta_1(2(4-b)^2((4+b)d-(3+b)t-1) + (-48+5b^2)d\beta_1 - 2b(b^2-8)d\beta_2)$,

$H_{23} = 2(4-b)^2((4+b)d-(3+b)t-1) + (5b^2-48)d\beta_2$,

$H_{24} = (1+b)(3+b)(3-b^2)$,

$H_{25} = 378 - 207b - 168b^2 - 76b^3 + 132b^4 + 38b^5 - 24b^6 - 12b^7 + 2b^8 + b^9$,

$H_{26} = -1296 + 936b + 630b^2 - 14b^3 - 434b^4 - 46b^5 + 82b^6 + 22b^7 - 6b^8 - 2b^9$,

$H_{27} = 1296 - 648b - 570b^2 - 7b^3 + 280b^4 + 23b^5 - 50b^6 - 9b^7 + 4b^8 + b^9$,

$H_{28} = 180 + 396b - 387b^2 - 198b^3 - 6b^4 + 194b^5 - 20b^6 - 42b^7 + 10b^8 + 2b^9 - b^{10}$,

$H_{29} = -360 - 936b + 1122b^2 + 114b^3 + 114b^4 - 374b^5 - 42b^6 + 118b^7 - 2b^8 - 10b^9$,

$H_{30} = 504 + 1080b - 1086b^2 - 300b^3 - 133b^4 + 286b^5 + 125b^6 - 80b^7 - 19b^8 + 6b^9 + b^{10}$.