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Strategic R&D Policy in a Quality-Differentiated Industry with More than Two Exporting Countries*

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Abstract

In this paper, we examine strategic R&D policy for quality-differentiated products in a third-market trade model. We extend the previous work by adding a third exporting country, so that the market structure is international triopoly. We show that the presence of the third exporting country affects strategic R&D policies. With three exporting countries, the lowest-quality exporting country gains from taxing domestic R&D and the middle-quality exporting country gains from subsidizing domestic R&D under both Bertrand and Cournot competition. As in the duopoly case, however, the unilaterally optimal policy for the highest-quality exporting country depends on the mode of competition. Various cases of policy coordination by exporting countries are also examined.

Keywords: strategic trade policy; R&D subsidy/tax; vertical differentiation; oligopoly.

JEL classification: F12; F13.

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1 Introduction

Since the seminal work by James Brander and Barbara Spencer (e.g., Spencer and Brander, 1983; Brander and Spencer, 1985) stimulated economists' interests in the strategic aspects of trade and industrial policy in the early 1980s, the literature on strategic trade policy has accumulated the enormous amount of knowledge on this subject and provided many policy implications over the past quarter century.[1] Subsidies on firms' research and development (R&D) activities are one of the policy instruments that have attracted the greatest deal of attention in the trade literature since Spencer and Brander (1983) have firstly examined its strategic use.[2]

In the literature of strategic trade policy, duopoly models have been extensively used. Although the oligopolistic market structure is sometimes assumed in each country, in most cases the number of competing countries is restricted to two.[3] Simplicity and tractability are great advantages of duopoly models. However, it is also important that implications from the analysis of duopoly models can be generalized to the cases in which more players are involved. A question is whether policy prescriptions regarding strategic trade and industrial policy obtained from the analysis of two competing countries are robust to the change in the number of competing countries. As long as firms produce homogenous goods, an increase in the number of competing countries has no specific effect on outcomes. However, as we will show in this paper, if firms produce quality-differentiated goods, strategic R&D policy is sensitive to the change in the number of competing countries.

Empirical studies show that in many industries goods are actually differentiated in quality. For example, using the NBER Trade Database, Hallak (2006) constructs export price indices for 3-digit sector, based on cross-country differences in export unit values of US imports in 1995 and 1996 at the

[1] A history of trade disputes at the General Agreement on Tariffs and Trade (GATT) and the World Trade Organization (WTO) proves that the governments of both developed and developing countries actually have various incentives to use trade and industrial policies. See Brander (1995) for the survey of the literature.

[2] The study on strategic R&D policy includes Bagwell and Staiger (1992, 1994), Miyagiwa and Ohno (1997), and Muniagurria and Singh (1997).

[3] To the best of our knowledge, the only exception is Lahiri and Ono (1997). They use a model in which there are many exporting and many importing countries. However, they do not address policy issues.

10-digit level of the Harmonized Tariff Schedule (HTS). The export price indices indicate a high variation across exporters and have a positive correlation with exporters' GDP per capita. For example, in the category of differentiated sectors, the indices of Switzerland and China are 1.64 and 0.63, respectively.[4] The average correlation between the sectoral index and GDP per capita is 0.45. Hummels and Klenow (2005) use United Nations Conference on Trade and Development (UNCTAD) Trade Analysis and Information System (TRAINS) data for 1995, covering 126 exporters to 59 markets at 6-digit level of the Harmonized System (HS) classification code. Their estimation shows that countries with twice GDP per worker tend to export 9 percent higher-quality varieties.

Moreover, some casual observations in the real world suggest that in many industries more than two major firms with possibly different nationalities compete in the global market. A typical example is the market for the dynamic random access memory (DRAM) chips in the semiconductor industry. South Korean companies (Samsung and Hynix) currently have the largest market share and a US company (Micron Technology), a Japanese company (Elpida Memory), and several Taiwanese companies share the remaining demand.[5] In March 2009, the Taiwanese government released a plan of merging domestic DRAM companies into Taiwan Memory Company (TMC) and forming a partnership with a Japanese company, Elpida. The Taiwanese and Japanese governments also plan to coordinate their policies and provide public funds to TMC and Elpida.

In this paper, we analyze how the presence of the third exporting country will alter the strategic incentive to subsidize or tax R&D in a quality-differentiated industry. We use a version of the standard model of vertical product differentiation with fixed cost of quality improvement, which has been extensively analyzed in the literature of industrial organization.[6] A number of papers have applied the vertical differentiation model to international trade and trade policy (e.g., Herguera et al., 2000, 2002; Jinji, 2003; Lutz, 2000; Motta et al., 1997; Park, 2001; Toshimitsu and Jinji, 2008; Zhou et al., 2002).

[4]Indices are normalized so that Canada has a value of 1.

[5]According to the data released by iSuppli, the shares in the global DRAM market in the first quarter of 2009 are as follows: Samsung (34%), Hynix (22%), Micron (15%), Elpida (14%), five Taiwanese companies (9%).

[6]See, for example, Mussa and Rosen (1978), Gabszewicz and Thisse (1979, 1980), Shaked and Sutton (1982, 1983), Ronen (1991), Aoki and Prusa (1997), Valletti (2000), Aoki (2003), and Toshimitsu (2003).

These papers restrict their attention to the case of duopoly competition with two exporting countries, with reciprocal trade between two countries, or with uni-directional trade. In particular, Park (2001) and Zhou et al. (2002) analyze strategic R&D policy for vertically differentiated products in a third-market trade model. Both of the two papers show that under Bertrand competition the government of the country that exports a high-quality (*resp.*, low-quality) product has a unilateral incentive to tax (*resp.* subsidize) domestic firm's R&D. Under Cournot competition, on the other hand, the government of the high-quality (*resp.*, low-quality) exporter has a unilateral incentive to subsidize (*resp.* tax) R&D. Zhou et al. (2002) also examine coordinated R&D policy by the two exporting countries and show that under Bertrand competition the government of the high-quality (*resp.*, low-quality) exporter should subsidize (*resp.* tax) R&D. Under Cournot competition, both governments should tax R&D. We extend the analysis by Park (2001) and Zhou et al. (2002) to the case of triopoly with three exporting countries and see how the unilaterally optimal and coordinated R&D policies would be affected.

The triopoly case under vertical differentiation is analyzed by Scarpa (1998) for the Bertrand competition and by Pezzino (2006) for the Cournot competition, though the focus of these two papers is on the effects of minimum quality standards. Neither paper considers an R&D subsidy. International trade is also assumed away. Thus, in this paper we apply their results to the case of international trade and investigate the role of strategic R&D policy.

The model involves a three stage game in which firms compete in two stages (quality choice and market competition) and prior to firms' decision governments set an R&D subsidy to maximize domestic welfare. We consider both price (Bertrand) and quantity (Cournot) competition at the final stage. We first examine the unilaterally optimal R&D policy for each exporting country. We then consider policy coordination by two or all exporting countries.[7] Under policy coordination, the governments of coordinating countries set their R&D subsidy to maximize their joint welfare.

The major findings of this paper are as follows. First, in comparison with the duopoly case, we find that the presence of the third exporting country changes the strategic policy for the country exporting

[7]As is seen in the example of the Taiwanese and Japanese governments' policies towards their DRAM companies, governments sometimes coordinate their policies in the real world.

the second-highest quality product from a tax to a subsidy on R&D when firms compete in quantities at the final stage. Second, we also find that the country that exports the lowest-quality product gains from an R&D tax under both Bertrand and Cournot competition. Third, the sign of the strategic policy (either subsidy or tax) depends on the mode of competition (either Bertrand or Cournot) only for the country that exports the highest-quality product. This result exhibits a sharp contrast to the outcome in the case of two exporting countries that, as Park (2001) and Zhou et al. (2002) show, a change in the mode of competition reverses strategic policies for both exporting countries.[8] Fourth, coordinated R&D policies by all exporting countries and by exporting countries of the high- and the middle-quality products are qualitatively similar to what Zhou et al. (2002) show in the case of two exporting countries. However, either of the exporting countries of the high- or the middle-quality products coordinates its R&D policy with the exporting country of the low-quality product, the R&D policy of the high- or the middle-quality exporter is qualitatively different from that in the duopoly case.

The rest of the paper is organized in the following way. In section 2, we explain the basic set-up of the model. We analyze strategic R&D policy in the case of three exporting countries and one importing country under Bertrand competition in section 3 and under Cournot competition in section 4. In section 5, we compare our results with those shown by the existing papers. In section 6, we examine policy coordination by exporting countries. In section 7, we conclude this paper.

2 The Model

The model we use in this paper is an extension of the standard model of vertically differentiation with fixed cost of quality improvement.[9] There are three exporting countries and one importing country. The exporting countries are labeled as country 1, 2, and 3. One firm is located in each exporting country. Each firm produces a quality-differentiated product and exports to the importing country. For

[8] As is well known, the sensitivity of the policy prescription to the mode of market competition has been one of the central questions in the literature of strategic trade policy. See, for example, Eaton and Grossman (1986).

[9] As for the standard model of vertical differentiation, see, e.g., Aoki and Prusa (1997), Aoki (2003), Ronen (1991), Toshimitsu (2003), and Valletti (2000).

simplicity, we assume that firms face identical cost structure. The marginal and average production costs are assumed to be constant and, for simplicity, are set equal to zero.[10] Each firm engages in product R&D to improve product quality. The cost of quality improvement for producing quality q is given by $F(q)$, where $F(0) = F'(0) = 0$, $F'(q) > 0$ and $F''(q) > 0$ for $q > 0$, $\lim_{q\to\infty} F'(q) = \infty$, and $F'''(q) \geq 0$.[11] For simplicity, we assume that there is no domestic consumption in each exporting country.

In the importing country, there is a continuum of consumers indexed by θ, which is uniformly distributed on $[0, 1]$ with density one. Each consumer is assumed to buy at most one unit of the quality-differentiated product. Consumer θ's (indirect) utility is given by $u = \theta q - p$ if he buys one unit of a product of quality $q \in [0, \infty)$ at price $p \in [0, \infty)$. His utility is zero if he buys nothing.

Firms compete in a two-stage game. In stage 1, firms simultaneously choose the quality of their products. In stage 2, firms compete in either prices or quantities in the market located in the importing country. Governments of the exporting countries commit to R&D subsidy policy in stage 0, prior to the game played by firms. We consider the unilaterally optimal R&D policy for each exporting country in sections 3 and 4 and policy coordination by two or all exporting countries in section 6. Throughout the paper, we restrict our attention to pure-strategy equilibria. We also focus on the interior solutions.

As is well known in the literature of vertical differentiation, firms choose to differentiate their product qualities in equilibrium in both Bertrand and Cournot cases. Let q_i be quality of the product produced by firm i, $i = 1, 2, 3$. Then, without loss of generality, we assume that $q_1 > q_2 > q_3$.

[10] This is a standard assumption in the literature. See, for example, Shaked and Sutton (1982, 1983) and Ronnen (1991).

[11] For analytical convenience, we assume the identical cost structure for all firms. In this case, there are three Nash equilibria, which are identical except for the identities of firms (and countries). As Zhou et al. (2002) show, we can rule out the possibility of multiple equilibria by assuming sufficient technology gap among firms. By doing so, the qualitative results will not change, but it becomes more complicated to calculate the numerical solutions under the particular functional form.

3 Strategic R&D Policy under Bertrand Competition

3.1 Firm behavior

We first analyze the case of Bertrand competition. As Scarpa (1998) shows, each firm's equilibrium revenue in stage 2 is given by

$$R^1(q_1,q_2,q_3) = \frac{q_2 q_3 (q_1-q_2)^2 (q_2-q_3)}{4\Delta^2}, \tag{1}$$

$$R^2(q_1,q_2,q_3) = \frac{(q_2)^2 (q_1-q_2)(q_2-q_3)(q_1-q_3)}{\Delta^2}, \tag{2}$$

$$R^3(q_1,q_2,q_3) = \frac{(q_1-q_2)(4q_1q_2-3q_2q_3-q_1q_3)^2}{4\Delta^2}, \tag{3}$$

where R^i is firm i's revenue and $\Delta \equiv 4q_1q_2 - 2q_2q_3 - q_1q_3 - (q_2)^2 > 0$. Partial derivatives of these revenue functions are reported in Appendix A.1.

In stage 1, each firm chooses its product quality to maximize its own profits, taking R&D subsidy/tax by the government and other firms' product qualities as given. Firm i's profits are given by $\pi^i(q_1,q_2,q_3;s_i) = R^i(q_1,q_2,q_3) - (1-s_i)F(q_i)$, $i = 1,2,3$, where $s_i < 1$ is an R&D subsidy from the government of country i. Note that a negative s_i means an R&D tax. The first-order condition (FOC) for firm 1, $\partial\pi^1(q_1,q_2,q_3;s_i)/\partial q_1 \equiv \pi^1_1(q_1,q_2,q_3;s_1) = 0$ gives a quality best-response function for firm 1, $q_1 = B^1(q_2,q_3;s_1)$. The quality best-response functions for firms 2 and 3 are obtained in a similar way. The Nash equilibrium in stage 1 is obtained by solving simultaneous equations $q_1 = B^1(q_2,q_3;s_1)$, $q_2 = B^2(q_1,q_3;s_2)$, and $q_3 = B^3(q_1,q_2;s_3)$.

As shown in Appendix A.2, the slopes of the quality best-response curves are as follows:

$$\frac{\mathrm{d}q_1}{\mathrm{d}q_2} = \frac{R^1_{13}R^3_{32} - R^1_{12}\pi^3_{33}}{\pi^1_{11}\pi^3_{33} - R^1_{13}R^3_{31}}, \qquad \frac{\mathrm{d}q_1}{\mathrm{d}q_3} = \frac{R^1_{12}R^2_{23} - R^1_{13}\pi^2_{22}}{\pi^1_{11}\pi^2_{22} - R^1_{12}R^2_{21}}, \tag{4}$$

$$\frac{\mathrm{d}q_2}{\mathrm{d}q_1} = \frac{R^2_{23}R^3_{31} - R^2_{21}\pi^3_{33}}{\pi^2_{22}\pi^3_{33} - R^2_{23}R^3_{32}}, \qquad \frac{\mathrm{d}q_2}{\mathrm{d}q_3} = \frac{R^2_{21}R^1_{13} - R^2_{23}\pi^1_{11}}{\pi^1_{11}\pi^2_{22} - R^1_{12}R^2_{21}}, \tag{5}$$

$$\frac{\mathrm{d}q_3}{\mathrm{d}q_1} = \frac{R^3_{32}R^2_{21} - R^3_{31}\pi^2_{22}}{\pi^2_{22}\pi^3_{33} - R^2_{23}R^3_{32}}, \qquad \frac{\mathrm{d}q_3}{\mathrm{d}q_2} = \frac{R^3_{31}R^1_{12} - R^3_{32}\pi^1_{11}}{\pi^1_{11}\pi^3_{33} - R^1_{13}R^3_{31}}, \tag{6}$$

where $R^1_{12} \equiv \partial^2 R^1/\partial q_1 \partial q_2$, $\pi^1_{11} \equiv \partial^2 \pi^1/(\partial q_1)^2$, and so on. This result shows that in this model the strategic relationship between any two products is affected by the reaction by a third product. For example, in the numerator of the right-hand side of $\mathrm{d}q_1/\mathrm{d}q_2$, the direct reaction of firm 1 to a marginal change in q_2 is measured by R^1_{12}. However, since q_3 also changes in response to a marginal change in q_2, firm 1 takes into account the indirect effect through a change in q_3, which is measured by $R^1_{13}R^3_{32}$. Thus, the overall strategic relationship of q_1 against q_2 depends on both the direct and indirect effects.

The signs of Eqs. (4)–(6) are generally ambiguous. Thus, we solve the model by assuming a particular functional form for $F(q_i)$. Since $F(q_i) = k(q_i)^2$, where $k > 0$, is most popularly used in the literature, we use this functional form. Product qualities at the unregulated equilibrium are $q_1^* \approx 0.1263/k$, $q_2^* \approx 0.02486/k$, and $q_3^* \approx 0.004765/k$.[12]

As shown by Eqs. (A.28)–(A.30) in Appendix A.2, we use the numerical results to evaluate the signs of the slope of the quality best-response functions at the unregulated equilibrium:

$$\mathrm{d}q_1/\mathrm{d}q_2 > 0,\ \mathrm{d}q_1/\mathrm{d}q_3 < 0,\ \mathrm{d}q_2/\mathrm{d}q_1 > 0,\ \mathrm{d}q_2/\mathrm{d}q_3 > 0,\ \mathrm{d}q_3/\mathrm{d}q_1 > 0,\ \mathrm{d}q_3/\mathrm{d}q_2 < 0. \tag{7}$$

It turns out that even in the case where the direct and indirect effects have opposite signs, the direct effect always dominates the indirect effect. Thus, the sign of the overall effect always coincides with that of the direct effect.

From this result, we know that for firm 1 (the high-quality producer) qualities are *strategic complements* against the middle-quality product but *strategic substitutes* against the low-quality product. For firm 2 (the middle-quality producer) qualities are *strategic complements* against both the high-quality and low-quality products. For firm 3 (the low-quality producer) qualities are *strategic complements* against the high-quality product but *strategic substitutes* against the middle-quality product.

Some of the results in (7) may not be intuitive. The reason why $\mathrm{d}q_1/\mathrm{d}q_3 < 0$ holds can be explained in the following way. The direct effect of an increase in q_3 on q_1 is negative, i.e., $R^1_{13} < 0$. As Scarpa (1998, pp. 669–671) also points out, an increase in q_3 (the lowest quality) makes the price competition more intense, which causes the marginal profitability of q_1 (the highest quality) to decrease. Consequently, the high-quality producer has an incentive to reduce its product quality in response to an increase in q_3. The indirect effect is, on the other hand, positive, because q_2 (the middle quality) increases in response to an increase in q_3, which causes q_1 to increase. However, the indirect effect is dominated by the direct effect and hence firm 1 reduces its product quality in response to an increase in q_3.

[12]Scarpa (1998) derives the same result in the case of $k = 1/2$.

3.2 Unilaterally optimal R&D policy

We now examine the R&D subsidy/tax policy set at stage 0. The government of country i chooses an R&D subsidy/tax on its domestic firm, s_i, to maximize domestic social welfare, W^i, which is given by

$$\begin{aligned} W^i(s_1,s_2,s_3) &= \pi^i(q_1(s_1,s_2,s_3),q_2(s_1,s_2,s_3),q_3(s_1,s_2,s_3),s_i) - s_iF(q_i(s_1,s_2,s_3)), \\ &= \left\{R^i(q_1(s_1,s_2,s_3),q_2(s_1,s_2,s_3),q_3(s_1,s_2,s_3)) - (1-s_i)F(q_i(s_1,s_2,s_3))\right\} \\ &\quad -s_iF(q_i(s_1,s_2,s_3)), \\ &= R^i(q_1(s_1,s_2,s_3),q_2(s_1,s_2,s_3),q_3(s_1,s_2,s_3)) - F(q_i(s_1,s_2,s_3)). \qquad (8) \end{aligned}$$

From the FOC for the government of country i to maximize W^i, $\mathrm{d}W^i/\mathrm{d}s_i = 0$, the unilaterally optimal R&D subsidy, s_i^*, is given by

$$s_1^* = \frac{R_2^1(\mathrm{d}q_2/\mathrm{d}q_1) + R_3^1(\mathrm{d}q_3/\mathrm{d}q_1)}{F'(q_1)}, \qquad (9)$$

$$s_2^* = \frac{R_1^2(\mathrm{d}q_1/\mathrm{d}q_2) + R_3^2(\mathrm{d}q_3/\mathrm{d}q_2)}{F'(q_2)}, \qquad (10)$$

$$s_3^* = \frac{R_1^3(\mathrm{d}q_1/\mathrm{d}q_3) + R_2^3(\mathrm{d}q_2/\mathrm{d}q_3)}{F'(q_3)}. \qquad (11)$$

As is clear from the above formulas, the subsidy/tax is determined by taking two rival firms' responses and their effects on the domestic rents. For example, in the numerator of the right-hand side in Eq. (9), $\mathrm{d}q_2/\mathrm{d}q_1$ and $\mathrm{d}q_3/\mathrm{d}q_1$ evaluate how firms 2 and 3 will respond to a marginal increase in q_1 and each term is multiplied by R_j^1, $j = 2, 3$, which measures the direct effect of a marginal change in the product quality of one rival firm on the domestic rents.

It can be shown (see Appendix A.1) that $R_2^1 < 0$, $R_3^1 < 0$, $R_1^2 > 0$, $R_3^2 < 0$, and $R_1^3 > 0$. Moreover, by assuming $F(q_i) = k(q_i)^2$, it holds that $R_2^3 < 0$ at the unregulated equilibrium (see Appendix A.2). The signs of $\mathrm{d}q_i/\mathrm{d}q_j$ are shown in Eq. (7). Substitute these results into Eqs. (9)–(11) to yield the signs of the unilaterally optimal R&D subsidies evaluated at the unregulated equilibrium:

$$s_1^* < 0, \quad s_2^* > 0, \quad \text{and} \quad s_3^* < 0.$$

From these values we obtain the following result:

Result 1 *Assume $F(q_i) = k(q_i)^2$, where $k > 0$. When firms compete in prices at stage 2, the unilaterally optimal policy is an R&D tax for both the country exporting the high-quality product and the country exporting the low-quality product and an R&D subsidy for the country exporting the middle-quality product.*

The above result can be explained by using Eqs. (9)–(11). The country exporting the high-quality product gains from an R&D tax because an increase in the product quality of either rival firm reduces country 1's domestic rents (i.e., $R_2^1 < 0$ and $R_3^1 < 0$) and qualities are *strategic complements* for either rival firm against the high-quality product (i.e., $\mathrm{d}q_2/\mathrm{d}q_1 > 0$ and $\mathrm{d}q_3/\mathrm{d}q_1 > 0$). An R&D tax enables firm 1 to commit to a lower level of quality than the quality level it chooses in the unregulated equilibrium, which raises country 1's domestic rents.

The reason for the R&D tax for the country that exports the low-quality product is slightly different. An increase in the product quality of the high-quality firm raises country 3's domestic rents (i.e., $R_1^3 > 0$) but an increase in the product quality of the middle-quality firm reduces country 3's domestic rents (i.e., $R_2^3 < 0$). In response to a marginal increase in q_3, the high-quality firm reduces its product quality (i.e., $\mathrm{d}q_1/\mathrm{d}q_3 < 0$) and the middle-quality firm raises its product quality (i.e., $\mathrm{d}q_2/\mathrm{d}q_3 > 0$). Thus, country 3 benefits from a commitment to a lower level of product quality than the quality level in the unregulated market. Consequently, an R&D tax is optimal for country 3.

As for the R&D subsidy for the country exporting the middle-quality product, an increase in the product quality of the high-quality firm increases country 2's domestic rents (i.e., $R_1^2 > 0$) but an increase in the product quality of the low-quality firm reduces country 2's domestic rents (i.e., $R_3^2 < 0$). The strategic relationship with the middle-quality product is *strategic complements* for the high-quality firm (i.e., $\mathrm{d}q_1/\mathrm{d}q_2 > 0$) and *strategic substitutes* for the low-quality firm (i.e., $\mathrm{d}q_3/\mathrm{d}q_2 < 0$). Thus, a commitment to a higher level of quality than the quality level in the unregulated market is beneficial to country 2. An R&D subsidy by the government of country 2 makes such a commitment credible.

4 Strategic R&D Policy under Cournot Competition

4.1 Firm behavior

We now turn to the case of Cournot competition. The process of the analysis is the same as that in the previous section. As Pezzino (2006) shows, each firm's equilibrium revenue in stage 2 is given by

$$R^{c1}(q_1, q_2, q_3) = \frac{q_1(4q_1q_2 - 2(q_2)^2 - q_1q_3)^2}{4\Phi^2}, \tag{12}$$

$$R^{c2}(q_1, q_2, q_3) = \frac{(q_1)^2 q_2(2q_2 - q_3)^2}{4\Phi^2}, \tag{13}$$

$$R^{c3}(q_1, q_2, q_3) = \frac{(q_1)^2(q_2)^2 q_3}{4\Phi^2}, \tag{14}$$

where R^{ci} is firm i's revenue and $\Phi \equiv 4q_1q_2 - (q_2)^2 - q_1q_3 > 0$. Partial derivatives of these revenue functions are reported in Appendix B.1.

In stage 1, each firm chooses its product quality to maximize its own profits, taking R&D subsidy/tax by the government and other firms' product qualities as given. Firm i's profits are given by $\Pi^i(q_1, q_2, q_3; s_i^c) = R^{ci}(q_1, q_2, q_3) - (1 - s_i^c)F(q_i)$, $i = 1, 2, 3$, where $s_i^c < 1$ is an R&D subsidy/tax from the government of country i. The FOC for firm 1, $\partial\Pi^1(q_1, q_2, q_3; s_i^c)/\partial q_1 \equiv \Pi_1^1(q_1, q_2, q_3; s_1^c) = 0$ gives a quality best-response function for firm 1, $q_1 = B^{c1}(q_2, q_3; s_1^c)$. The quality best-response functions for firms 2 and 3 are obtained in a similar way. The Nash equilibrium in stage 1 is obtained by solving these quality best-response functions.

As shown in Appendix B.2, the slopes of the quality best-response curves are as follows:

$$\frac{\mathrm{d}q_1}{\mathrm{d}q_2} = \frac{R_{13}^{c1}R_{32}^{c3} - R_{12}^{c1}\Pi_{33}^3}{\Pi_{11}^1\Pi_{33}^3 - R_{13}^{c1}R_{31}^{c3}}, \qquad \frac{\mathrm{d}q_1}{\mathrm{d}q_3} = \frac{R_{12}^{c1}R_{23}^{c2} - R_{13}^{c1}\Pi_{22}^2}{\Pi_{11}^1\Pi_{22}^2 - R_{12}^{c1}R_{21}^{c2}}, \tag{15}$$

$$\frac{\mathrm{d}q_2}{\mathrm{d}q_1} = \frac{R_{23}^{c2}R_{31}^{c3} - R_{21}^{c2}\Pi_{33}^3}{\Pi_{22}^2\Pi_{33}^3 - R_{23}^{c2}R_{32}^{c3}}, \qquad \frac{\mathrm{d}q_2}{\mathrm{d}q_3} = \frac{R_{21}^{c2}R_{13}^{c1} - R_{23}^{c2}\Pi_{11}^1}{\Pi_{11}^1\Pi_{22}^2 - R_{12}^{c1}R_{21}^{c2}}, \tag{16}$$

$$\frac{\mathrm{d}q_3}{\mathrm{d}q_1} = \frac{R_{32}^{c3}R_{21}^{c2} - R_{31}^{c3}\Pi_{22}^2}{\Pi_{22}^2\Pi_{33}^3 - R_{23}^{c2}R_{32}^{c3}}, \qquad \frac{\mathrm{d}q_3}{\mathrm{d}q_2} = \frac{R_{31}^{c3}R_{12}^{c1} - R_{32}^{c3}\Pi_{11}^1}{\Pi_{11}^1\Pi_{33}^3 - R_{13}^{c1}R_{31}^{c3}}, \tag{17}$$

where $R_{12}^{c1} \equiv \partial^2 R^{c1}/\partial q_1 \partial q_2$, $\Pi_{11}^1 \equiv \partial^2\Pi^1/(\partial q_1)^2$, and so on. As in the Bertrand case, the signs of Eqs. (15)–(17) are generally ambiguous. Thus, we solve the model by using $F(q_i) = k(q_i)^2$, where $k > 0$. Product qualities at the unregulated equilibrium are $q_1^* \approx 0.1261/k$, $q_2^* \approx 0.04473/k$, and $q_3^* \approx 0.01305/k$.[13]

[13] Pezzino (2006) derives the same result.

As shown by Eqs. (B.28)–(B.30) in Appendix B.2, we use the numerical results to evaluate the signs of the slope of the quality best-response functions at the unregulated equilibrium:

$$\mathrm{d}q_1/\mathrm{d}q_2 > 0,\ \mathrm{d}q_1/\mathrm{d}q_3 > 0,\ \mathrm{d}q_2/\mathrm{d}q_1 < 0,\ \mathrm{d}q_2/\mathrm{d}q_3 < 0,\ \mathrm{d}q_3/\mathrm{d}q_1 < 0,\ \mathrm{d}q_3/\mathrm{d}q_2 < 0. \tag{18}$$

Similar to the Bertrand case, the direct effect determines the sign of the slope of the quality best-response function in all cases by dominating the indirect effect.

From this result, we know that for firm 1 (the high-quality producer) qualities are *strategic complements* against both the middle-quality and low-quality products. For firms 2 and 3 qualities are always *strategic substitutes.*

An explanation may be required for the result of $\mathrm{d}q_2/\mathrm{d}q_3 < 0$. In fact, the direct and indirect effects are both negative in this case. With regard to the direct effect, an increase in q_3 reduces the marginal revenue of firm 2, i.e., $R^{c2}_{23} < 0$. This is because (given q_1) an increase in q_3 (the lowest quality) reduces the marginal profitability of q_2 (the middle quality) by lowering the degree of differentiation between q_2 and q_3. As for the indirect effect, firm 1 responds to an increase in q_3 by increasing q_1, which also reduces the marginal profitability of q_2 by lowering the relative quality level of q_2. As a result, q_3 is treated as a strategic substitute by firm 2.

4.2 Unilaterally optimal R&D policy

We now examine the R&D subsidy/tax policy set at stage 0. Social welfare of country i is given by

$$\begin{aligned} W^{ci}(s^c_1, s^c_2, s^c_3) &= \Pi^i(q_1(s^c_1, s^c_2, s^c_3), q_2(s^c_1, s^c_2, s^c_3), q_3(s^c_1, s^c_2, s^c_3), s^c_i) - s^c_i F(q_i(s^c_1, s^c_2, s^c_3)), \\ &= R^i(q_1(s^c_1, s^c_2, s^c_3), q_2(s^c_1, s^c_2, s^c_3), q_3(s^c_1, s^c_2, s^c_3)) - F(q_i(s^c_1, s^c_2, s^c_3)). \end{aligned} \tag{19}$$

From the FOC for the government of country i to maximize W^{ci}, $\mathrm{d}W^{ci}/\mathrm{d}s^c_i = 0$, the unilaterally optimal R&D subsidy/tax for country i, s^{c*}_i, is given by

$$s^{c*}_1 = \frac{R^{c1}_2(\mathrm{d}q_2/\mathrm{d}q_1) + R^{c1}_3(\mathrm{d}q_3/\mathrm{d}q_1)}{F'(q_1)}, \tag{20}$$

$$s^{c*}_2 = \frac{R^{c2}_1(\mathrm{d}q_1/\mathrm{d}q_2) + R^{c2}_3(\mathrm{d}q_3/\mathrm{d}q_2)}{F'(q_2)}, \tag{21}$$

$$s^{c*}_3 = \frac{R^{c3}_1(\mathrm{d}q_1/\mathrm{d}q_3) + R^{c3}_2(\mathrm{d}q_2/\mathrm{d}q_3)}{F'(q_3)}. \tag{22}$$

It can be shown (see Appendix B.1) that $R_2^{c1} < 0$, $R_3^{c1} < 0$, $R_1^{c2} < 0$, $R_3^{c2} < 0$, and $R_1^{c3} < 0$. Moreover, by assuming $F(q_i) = k(q_i)^2$, it holds that $R_2^{c3} > 0$ at the unregulated equilibrium (see Appendix B.2). The signs of $\mathrm{d}q_i/\mathrm{d}q_j$ are shown in Eq. (18). Substitute these results into Eqs. (20)–(22) to yield the signs of the unilaterally optimal R&D subsidies evaluated at the unregulated equilibrium:

$$s_1^{c*} > 0, \quad s_2^{c*} > 0, \quad \text{and} \quad s_3^{c*} < 0.$$

From these values we obtain the following result:

Result 2 *Assume $F(q_i) = k(q_i)^2$, where $k > 0$. When firms compete in quantities at stage 2, the unilaterally optimal policy is an R&D subsidy for both the country exporting the high-quality product and the country exporting the middle-quality product and an R&D tax for the country exporting the low-quality product.*

The reasons for this result can be understood with the help of Eqs. (20)–(22). First, the country exporting the high-quality product can earn higher domestic rents by subsidizing domestic firm's R&D. This is because an increase in the product quality of either rival firm has a negative effect on country 1's domestic rents (i.e., $R_2^{c1} < 0$ and $R_3^{c1} < 0$). However, either rival firm will respond by reducing its product quality when firm 1 increases q_1 (i.e., $\mathrm{d}q_2/\mathrm{d}q_1 < 0$ and $\mathrm{d}q_3/\mathrm{d}q_1 < 0$). Therefore, country 1 can earn higher rents by committing to a higher product quality than the quality level in the unregulated equilibrium. The government of country 1 can help firm 1 to make such a commitment by providing an R&D subsidy.

Second, the country exporting the middle-quality product gains from an R&D subsidy for the following reason. Similar to country 1's case, an increase in the product quality of either rival firm has a harmful effect on country 2's domestic rents (i.e., $R_1^{c2} < 0$ and $R_3^{c2} < 0$). However, the strategic relationship with the middle-quality product is *strategic complements* for the high-quality firm (i.e., $\mathrm{d}q_1/\mathrm{d}q_2 > 0$) and *strategic substitutes* for the low-quality firm (i.e., $\mathrm{d}q_3/\mathrm{d}q_2 < 0$). Thus, from the view point of the relationship with the high-quality product, a commitment to a lower product quality than the quality level in the unregulated equilibrium is beneficial to country 2. On the other hand, from the view point of the relationship with the low-quality product, a commitment to a higher product quality than the quality level in the unregulated equilibrium is beneficial to country 2. Since the second effect dominates the first (see the result in Appendix B.2), an R&D subsidy is optimal for country 2.

Finally, an increase in the product quality of the high-quality firm reduces firm 3's profits (i.e., $R_1^{c3} < 0$) but an increase in the product quality of the middle-quality firm raises country 3's domestic rents (i.e., $R_2^{c3} > 0$). The strategic relationship with the low-quality product is *strategic complements* for the high-quality firm (i.e., $\mathrm{d}q_1/\mathrm{d}q_3 > 0$) and *strategic substitutes* for the middle-quality firm (i.e., $\mathrm{d}q_2/\mathrm{d}q_3 < 0$). Thus, a commitment to a lower level of product quality than the quality level in the unregulated market improves country 3's domestic rents. Such a commitment is credible under the R&D tax by the government of country 3.

A comparison between Results 1 and 2 yields the following result:

Result 3 *The unilaterally optimal policy is an R&D subsidy for the country exporting the middle-quality product and an R&D tax for the country exporting the low-quality product, regardless of the mode of competition at the final stage. On the other hand, the unilaterally optimal policy for the country exporting the high-quality product is an R&D tax under Bertrand competition and an R&D subsidy under Cournot competition.*

Therefore, the policy prescription is robust for countries 2 and 3, while it depends on the mode of competition for country 1.

5 Discussion

In this section, we compare the above results with those shown by the existing papers. Before considering the strategic R&D policies, it is useful to make a comparison between the duopoly case and the triopoly case in the unregulated equilibrium. Table 1 shows Nash equilibrium product qualities and corresponding threshold taste parameters in the unregulated market under Bertrand and Cournot competition for both duopoly and triopoly cases. These outcomes are obtained by using a particular cost function $F(q_i) = k(q_i)^2$. In this table, θ_1 is a taste parameter that makes indifferent between product 1 and product 2. Similarly, θ_2 is a taste parameter that makes indifferent between product 2 and product 3, and θ_3 makes indifferent between product 3 and no purchase. Thus, the demand for products 1, 2, and 3 are respectively given by $x_1 = 1 - \theta_1$, $x_2 = \theta_1 - \theta_2$, and $x_3 = \theta_2 - \theta_3$.

Table 1: Unregulated Outcomes: Duopoly and Triopoly

		q_1^*	q_2^*	q_3^*	θ_1	θ_2	θ_3
Bertrand	Duopoly	$0.1267/k$	$0.02412/k$	–	0.4750	0.2125	–
	Triopoly	$0.1263/k$	$0.02486/k$	$0.004765/k$	0.4775	0.2054	0.09180
Cournot	Duopoly	$0.1260/k$	$0.04511/k$	–	0.5492	0.2746	–
	Triopoly	$0.1261/k$	$0.04473/k$	$0.01305/k$	0.5529	0.2982	0.1491

If one compares between the duopoly case and the triopoly case for each mode of competition, he will notice that the low-quality product in the duopoly case actually corresponds to the middle-quality product in the triopoly case. In particular, under Bertrand competition, any consumers who buy product 3 in the triopoly case do not consume the quality-differentiated product in the duopoly case. This property suggests that when we compare the R&D policies in the triopoly case with those in the duopoly case, we should compare country 2's policy in these two cases (rather than compare country 3's policy in triopoly with country 2's in duopoly).

Table 2 summarizes the strategic R&D policies for the duopoly and triopoly cases under both Bertrand and Cournot competition. The strategic R&D policies in the duopoly case are taken from Zhou et al. (2002) and Park (2001).

Table 2: Strategic R&D Policy: Duopoly and Triopoly

		Country 1	Country 2	Country 3
Bertrand	Duopoly	tax	subsidy	–
	Triopoly	tax	subsidy	tax
Cournot	Duopoly	subsidy	tax	–
	Triopoly	subsidy	subsidy	tax

The summary in Table 2 indicates that comparing the triopoly case with the duopoly case, the policy reversal due to the presence of the third exporting country occurs only for country 2 under Cournot competition. The presence of the third exporting country does not alter the policy prescriptions for other cases. From the above examination, we obtain the following result:

Result 4 *The presence of the third exporting country that produces the lowest-quality product changes the direction of strategic R&D policy from a tax to a subsidy for the second-highest-quality exporting country under Cournot competition. By contrast, the presence of the third exporting country does not change the direction of strategic R&D policy for the highest-quality exporting country.*

Note that, unlike the duopoly case analyzed by Zhou et al. (2002) and Park (2001), the policy reversal due to the model of competition is observed only for the highest-quality exporting country in the case of international triopoly. The existing papers show that the policy reversal occurs for both countries in the case of international duopoly.

6 Policy Coordination

In this section, we consider policy coordination by exporting countries. Under policy coordination, coordinating countries choose their R&D subsidies to maximize their joint welfare. In the case of policy coordination by two exporting countries j and k, these countries solve the following maximization problem: $\max_{\{s_j,s_k\}} W^j(s_1,s_2,s_3)+W^k(s_1,s_2,s_3)$. In the case of policy coordination by all exporting countries, on the other hand, the exporting countries solve the following maximization problem: $\max_{\{s_1,s_2,s_3\}} \sum_{i=1}^{3} W^i(s_1,s_2,s_3)$. There are four cases of policy coordination by choosing different combinations of countries. Three cases can be obtained by considering only two of the three exporting countries coordinate their R&D policy. The fourth case is obtained by considering policy coordination by all of the three exporting countries.

Table 3 shows the result in both Bertrand and Cournot cases. All calculations are provided in Appendix C. As in the previous sections, we assume $F(q_i) = k(q_i)^2$ to obtain concrete results. Policy coordination in the case of duopoly shown by Zhou et al. (2002) is also included in Table 3 for reference.

Table 3: R&D Policy Coordination

		Coordinating Countries	$\hat{s}_1$	$\hat{s}_2$	$\hat{s}_3$
Bertrand	Duopoly		subsidy	tax	–
	Triopoly	Countries 1 & 2	subsidy	tax	–
		Countries 1 & 3	tax	–	tax
		Countries 2 & 3	–	tax	tax
		All Countries	subsidy	tax	tax
Cournot	Duopoly		tax	tax	–
	Triopoly	Countries 1 & 2	tax	tax	–
		Countries 1 & 3	subsidy	–	tax
		Countries 2 & 3	–	subsidy	tax
		All Countries	tax	tax	tax

As shown in Table 3, coordinated policies by countries 1 and 2 agree with those in the case of duopoly in both Bertrand and Cournot cases. This result can be explained in the following way. In the case of triopoly market, coordinated policies are determined by the relative strength of two factors: (i) internalization of the external effects on the partner country's (countries') welfare; and (ii) strategic relationship with the outside country. Compared to unilateral policies, policy coordination internalizes the effects of their policies on the partner country's (countries') welfare. This is the first factor. However, if one of the three countries is excluded from the policy coordination, coordinated policies need to reflect strategic relationship with the excluded country, just like unilateral policies. This is the second factor. In the case of policy coordination by countries 1 and 2, since the effects of country 3 (the lowest-quality exporter) on them are quite small, coordinated policies are mainly determined by the internalization factor. Therefore, the signs of the coordinated policies by countries 1 and 2 coincide with those in the case of duopoly. A similar logic applied to the case of policy coordination by all exporting countries. In that case, the signs of R&D policies by countries 1 and 2 are the same as those in the case of policy coordination by countries 1 and 2 in both Bertrand and Cournot cases.

In any cases of policy coordination, an R&D tax is required for country 3, which is the same as the unilaterally optimal policy (see Tables 2 and 3). This is mainly because an R&D tax on firm 3 increases firm 3's profits by reducing q_3 and making firm 3's products more preferable to those who have lower willingness to pay for quality. At the same time, a decrease in q_3 due to an R&D tax is also beneficial to the partner country (countries) of policy coordination, because products are more differentiated. Thus, an R&D tax is always required for country 3.

Moreover, when country 1 coordinates its R&D policy with country 3, the sign of its R&D policy coincides with that of the unilaterally optimal policy in both Bertrand and Cournot cases (see Tables 2 and 3). The reason is that the strategic relationship with country 2 is more important than the external effect on country 3's welfare. When country 2 coordinates its R&D policy with country 3, on the other hand, the sign of its R&D policy coincides with that of the unilaterally optimal policy in the Cournot case but is reversed in the Bertrand case (see Tables 2 and 3). The reason is as follows. In the Bertrand case, the competition is so fierce that the strategic relationship with country 1 is important for country 2 to determine its unilaterally optimal policy. Under the policy coordination, country 2 needs to take into account the effect of the competition between firms 1 and 2 on country 3. The internalization of the external effect on country 3 is relatively more important for country 2 in the coordinated policy. Thus, its R&D policy is reversed from subsidy to tax by internalizing the external effect on country 3.[14] In the Cournot case, by contrast, since the competition is not so fierce, the strategic relationship with country 1 is less important for country 2 to determine its unilaterally optimal policy. Thus, an R&D subsidy is unilaterally optimal, which is different from that in the case of duopoly. The same is true for country 2's coordinated policy with country 3. Since the strategic relationship with country 1 is less important and country 3 directly benefits from an increase in q_2, an R&D subsidy is still required for

[14] One may wonder why an R&D tax is required for country 2 in the policy coordination between countries 2 and 3, because it seems that a decrease in q_2 due to an R&D tax makes the price competition between firms 2 and 3 stronger. In fact, this is not true. It holds that $R_2^3 < 0$. For firm 2, the price competition with firm 1 is more important. By decreasing q_2, firm 2 can soften the price competition with firm 1. Then, Country 3 benefits from the softened price competition between countries 1 and 2, even if the degree of quality differentiation is reduced between q_2 and q_3. Notice that although an R&D tax is also required for country 2 in the policy coordination between countries 1 and 2, the reason is different.

country 2 when the external effect on country 3 is internalized.

The findings in Table 3 are summarized as follows:

Result 5 *Assume $F(q_i) = k(q_i)^2$, where $k > 0$. Consider policy coordination by exporting countries. (i) When firms compete in prices at stage 2, the country exporting the high-quality product should subsidize R&D if it coordinates policy with the country exporting the middle-quality product or with other two exporting countries. In all other cases, R&D should be taxed. (ii) When firms compete in quantities at stage 2, if either the country exporting the high-quality product or the country exporting the middle-quality product coordinates policy with the country exporting the low-quality product, the high- or middle-quality exporter should subsidize R&D. In all other cases, R&D should be taxed.*

7 Conclusions

In this paper, we analyze strategic policy towards domestic firm's R&D activity in an industry where goods are differentiated in quality. The novelty of this paper is to identify the nature of strategic R&D policy when there are three exporting countries. We show difference and similarity in such a policy between the case of duopoly and the case of triopoly. We use a version of the standard model of vertical product differentiation with fixed cost of quality improvement. The fixed cost of quality improvement is interpreted as R&D cost, which is sunk when firms choose prices or outputs.

This paper provides an additional insight into strategic trade policy by showing that policy prescription may depend on the number of competing exporting countries. This aspect of strategic policy has not been investigated in the literature, since it is irrelevant as long as the assumption of homogenous goods is maintained. However, since quality differentiation and R&D activities have become more and more important parts of firms' activities as globalization intensifies international competition, we believe that the direction of investigation we suggest in this paper is worth pursuing further.

Appendix

A Bertrand Competition

A.1 Partial derivatives of the revenue functions

The first-order partial derivatives of the revenue functions are as follows:

$$R_1^1 = \frac{4q_1q_2 - 3q_2q_3 - q_1q_3}{4\Delta^3}\left\{16(q_1)^2(q_2)^2 + (q_1)^2(q_3)^2 - 8(q_1)^2q_2q_3 - 12q_1(q_2)^3 - 9q_1(q_2)^2q_3 + 3q_1q_2(q_3)^2 + 8(q_2)^4 - 7(q_2)^3q_3 + 8(q_2)^2(q_3)^2\right\}, \tag{A.1}$$

$$R_2^1 = -\frac{4q_1q_2 - q_1q_3 - 3q_2q_3}{4\Delta^3}\left\{8(q_1)^2(q_2)^2 - (q_1)^2(q_3)^2 - 4(q_1)^2q_2q_3 + 4q_1(q_2)^3 - 17q_1(q_2)^2q_3 + 7q_1q_2(q_3)^2 - 3(q_2)^3q_3 + 6(q_2)^2(q_3)^2\right\} < 0, \tag{A.2}$$

$$R_3^1 = -\frac{3(q_2)^2(q_1-q_2)^2(4q_1q_2 - q_1q_3 - 3q_2q_3)}{2\Delta^3} < 0, \tag{A.3}$$

$$R_1^2 = \frac{(q_2)^2(q_2-q_3)^2\left\{2q_1q_2 + q_1q_3 + (q_2)^2 - 4q_2q_3\right\}}{\Delta^3} > 0, \tag{A.4}$$

$$R_2^2 = \frac{q_2(q_1-q_3)}{\Delta^3}\left\{4(q_1)^2(q_2)^2 + 2(q_1)^2(q_3)^2 - 3(q_1)^2q_2q_3 - 7q_1(q_2)^3 + 4q_1(q_2)^2q_3 - 3q_1q_2(q_3)^2 + 5(q_2)^3q_3 - 2(q_2)^2(q_3)^2\right\}, \tag{A.5}$$

$$R_3^2 = -\frac{(q_2)^2(q_1-q_2)^2\left\{2q_1q_2 + q_1q_3 + (q_2)^2 - 4q_2q_3\right\}}{\Delta^3} < 0, \tag{A.6}$$

$$R_1^3 = \frac{3(q_2)^2q_3(q_1-q_2)(q_2-q_3)^2}{2\Delta^3} > 0, \tag{A.7}$$

$$R_2^3 = -\frac{q_3(q_1-q_2)}{4\Delta^3}\left\{6q_1(q_2)^3 - 2(q_1)^2q_2q_3 - (q_1)^2(q_3)^2 - 5q_1(q_2)^2q_3 + 5q_1q_2(q_3)^2 - 5(q_2)^3q_3 + 2(q_2)^2(q_3)^2\right\}, \tag{A.8}$$

$$R_3^3 = \frac{(q_2)^2(q_1-q_2)^2\left\{4q_1q_2 + 4q_2q_3 - 7q_1q_3 - (q_2)^2\right\}}{4\Delta^3}, \tag{A.9}$$

where $R_2^1 \equiv \partial R^1/\partial q_2$ and so on.

The signs of R_1^1, R_2^2, R_2^3, and R_3^3 are ambiguous. However, for interior solutions, $R_1^1 > 0$, $R_2^2 > 0$, and $R_3^3 > 0$ must hold. Thus, from (A.1), (A.5), and (A.9), we impose the following assumptions:

$$16(q_1)^2(q_2)^2+(q_1)^2(q_3)^2-8(q_1)^2q_2q_3-12q_1(q_2)^3-9q_1(q_2)^2q_3+3q_1q_2(q_3)^2+8(q_2)^4-7(q_2)^3q_3+8(q_2)^2(q_3)^2 > 0$$

$$4(q_1)^2(q_2)^2 + 2(q_1)^2(q_3)^2 - 3(q_1)^2q_2q_3 - 7q_1(q_2)^3 + 4q_1(q_2)^2q_3 - 3q_1q_2(q_3)^2 + 5(q_2)^3q_3 - 2(q_2)^2(q_3)^2 > 0$$

$$4q_1q_2 + 4q_2q_3 - 7q_1q_3 - (q_2)^2 > 0.$$

The second-order partial derivatives of the revenue functions are as follows:

$$R^1_{11} = -\frac{(q_2)^2(4q_2 - q_3)(q_2 - q_3)^2 \left\{20q_1q_2 - 5q_1q_3 - 19q_2q_3 + 4(q_2)^2\right\}}{2\Delta^4} < 0, \tag{A.10}$$

$$R^1_{12} = \frac{q_2(q_2 - q_3)\left\{20q_1q_2 - 19q_2q_3 - 5q_1q_3 + 4(q_2)^2\right\}}{2\Delta^4}\left\{4q_1(q_2)^2 - 2q_1q_2q_3 + q_1(q_3)^2 - 3(q_2)^2q_3\right\} > 0, \tag{A.11}$$

$$R^1_{13} = -\frac{3(q_2)^3(q_1 - q_2)(q_2 - q_3)\left\{20q_1q_2 - 5q_1q_3 - 19q_2q_3 + 4(q_2)^2\right\}}{2\Delta^4} < 0, \tag{A.12}$$

$$R^2_{21} = -\frac{2q_2(q_2 - q_3)}{\Delta^4}\left\{-8(q_1)^2(q_2)^3 + 3(q_1)^2(q_2)^2q_3 - 3(q_1)^2q_2(q_3)^2 - 7q_1(q_2)^4 + 27q_1(q_2)^3q_3 - 9q_1(q_2)^2(q_3)^2 + 7q_1q_2(q_3)^3 + 6(q_2)^4q_3 - 15(q_2)^3(q_3)^2\right\}, \tag{A.13}$$

$$R^2_{22} = -\frac{2(q_1 - q_3)}{\Delta^4}\left\{5(q_1)^3q_2(q_3)^2 + (q_1)^3(q_3)^3 + 8(q_1)^2(q_2)^4 - 8(q_1)^2(q_2)^3q_3 - 2(q_1)^2(q_2)^2(q_3)^2 - 7(q_1)^2q_2(q_3)^3 + 7q_1(q_2)^5 - 23q_1(q_2)^4q_3 + 16q_1(q_2)^3(q_3)^2 - 5(q_2)^5q_3 + 8(q_2)^4(q_3)^2\right\}, \tag{A.14}$$

$$R^2_{23} = \frac{2q_2(q_1 - q_2)}{\Delta^4}\left\{5(q_1)^3q_2q_3 + (q_1)^3(q_3)^2 + 3(q_1)^2(q_2)^3 - 3(q_1)^2(q_2)^2q_3 - 9(q_1)^2q_2(q_3)^2 + 6q_1(q_2)^4 - 15q_1(q_2)^3q_3 + 9q_1(q_2)^2(q_3)^2 - 5(q_2)^4q_3 + 8(q_2)^3(q_3)^2\right\}, \tag{A.15}$$

$$R^3_{31} = \frac{3(q_2)^3(q_1 - q_2)(q_2 - q_3)\left\{4q_1q_2 - 10q_1q_3 + 7q_2q_3 - (q_2)^2\right\}}{2\Delta^4}, \tag{A.16}$$

$$R^3_{32} = \frac{q_2(q_1 - q_2)}{2\Delta^4}\left\{8(q_1)^3q_2q_3 + 7(q_1)^3(q_3)^2 - 12(q_1)^2(q_2)^3 + 12(q_1)^2(q_2)^2q_3 - 27(q_1)^2q_2(q_3)^2 + 3q_1(q_2)^4 + 3q_1(q_2)^3q_3 + 3q_1(q_2)^2(q_3)^2 - 5(q_2)^4q_3 + 8(q_2)^3(q_3)^2\right\}, \tag{A.17}$$

$$R^3_{33} = -\frac{(q_2)^2(q_1 - q_2)^2}{2\Delta^4}\left\{8(q_1)^2q_2 + 7(q_1)^2q_3 - 22q_1(q_2)^2 + 10q_1q_2q_3 + 5(q_2)^3 - 8(q_2)^2q_3\right\}, \tag{A.18}$$

where $R^1_{12} \equiv \partial^2 R^1/\partial q_1 \partial q_2$ and so on.

A.2 Quality best-response functions

Quality best-response curves in stage 1 are given by the first-order conditions (FOCs) for firms to maximize profits: $\pi^1_1 = 0$, $\pi^2_2 = 0$, and $\pi^3_3 = 0$.Totally differentiate $\pi^1_1 = 0$ to obtain the slopes of the quality best-response curve for firm 1 in quality space:

$$\frac{\mathrm{d}q_1}{\mathrm{d}q_2} = -\frac{R^1_{12} + R^1_{13}(\mathrm{d}q_3/\mathrm{d}q_2)}{\pi^1_{11}}, \tag{A.19}$$

$$\frac{\mathrm{d}q_1}{\mathrm{d}q_3} = -\frac{R^1_{12}(\mathrm{d}q_2/\mathrm{d}q_3) + R^1_{13}}{\pi^1_{11}}. \tag{A.20}$$

Similarly, totally differentiate $\pi_2^2 = 0$ to obtain the slopes of the quality best-response curve for firm 2:

$$\frac{\mathrm{d}q_2}{\mathrm{d}q_1} = -\frac{R_{21}^2 + R_{23}^2(\mathrm{d}q_3/\mathrm{d}q_1)}{\pi_{22}^2}, \tag{A.21}$$

$$\frac{\mathrm{d}q_2}{\mathrm{d}q_3} = -\frac{R_{21}^2(\mathrm{d}q_1/\mathrm{d}q_3) + R_{23}^2}{\pi_{22}^2}. \tag{A.22}$$

Moreover, totally differentiate $\pi_3^3 = 0$ to obtain the slopes of the quality best-response curve for firm 3:

$$\frac{\mathrm{d}q_3}{\mathrm{d}q_1} = -\frac{R_{31}^3 + R_{32}^3(\mathrm{d}q_2/\mathrm{d}q_1)}{\pi_{33}^3}, \tag{A.23}$$

$$\frac{\mathrm{d}q_3}{\mathrm{d}q_2} = -\frac{R_{31}^3(\mathrm{d}q_1/\mathrm{d}q_2) + R_{32}^3}{\pi_{33}^3}. \tag{A.24}$$

From (A.19) and (A.24) it yields that

$$\frac{\mathrm{d}q_1}{\mathrm{d}q_2} = \frac{R_{13}^1 R_{32}^3 - R_{12}^1 \pi_{33}^3}{\pi_{11}^1 \pi_{33}^3 - R_{13}^1 R_{31}^3}, \qquad \frac{\mathrm{d}q_3}{\mathrm{d}q_2} = \frac{R_{31}^3 R_{12}^1 - R_{32}^3 \pi_{11}^1}{\pi_{11}^1 \pi_{33}^3 - R_{13}^1 R_{31}^3}. \tag{A.25}$$

Similarly, from (A.20) and (A.22) it yields that

$$\frac{\mathrm{d}q_1}{\mathrm{d}q_3} = \frac{R_{12}^1 R_{23}^2 - R_{13}^1 \pi_{22}^2}{\pi_{11}^1 \pi_{22}^2 - R_{12}^1 R_{21}^2}, \qquad \frac{\mathrm{d}q_2}{\mathrm{d}q_3} = \frac{R_{21}^2 R_{13}^1 - R_{23}^2 \pi_{11}^1}{\pi_{11}^1 \pi_{22}^2 - R_{12}^1 R_{21}^2}. \tag{A.26}$$

Finally, from (A.21) and (A.23) it yields that

$$\frac{\mathrm{d}q_2}{\mathrm{d}q_1} = \frac{R_{23}^2 R_{31}^3 - R_{21}^2 \pi_{33}^3}{\pi_{22}^2 \pi_{33}^3 - R_{23}^2 R_{32}^3}, \qquad \frac{\mathrm{d}q_3}{\mathrm{d}q_1} = \frac{R_{32}^3 R_{21}^2 - R_{31}^3 \pi_{22}^2}{\pi_{22}^2 \pi_{33}^3 - R_{23}^2 R_{32}^3}. \tag{A.27}$$

Under the assumption of $F(q_i) = k(q_i)^2$, where $k > 0$, we can solve the model to obtain product qualities at the unregulated equilibrium: $q_1^* \approx 0.1263/k$, $q_2^* \approx 0.02486/k$, and $q_3^* \approx 0.004765/k$. Substitute these values into Eqs. (A.1)–(A.18) to yield

$$\begin{array}{lll}
R_1^1 \approx 0.2527, & R_2^1 \approx -0.1542, & R_3^1 \approx -0.08085, \\
R_1^2 \approx 0.001281, & R_2^2 \approx 0.04971, & R_3^2 \approx -0.03263, \\
R_1^3 \approx 0.0001318, & R_2^3 \approx -0.0004992, & R_3^3 \approx 0.009536, \\
R_{11}^1 \approx -0.04661k, & R_{12}^1 \approx 0.2724k, & R_{13}^1 \approx -0.1854k, \\
R_{21}^2 \approx 0.1278k, & R_{22}^2 \approx -0.7710k, & R_{23}^2 \approx 0.6348k, \\
R_{31}^3 \approx 0.02086k, & R_{32}^3 \approx -0.01814k, & R_{33}^3 \approx -0.4585k,
\end{array}$$

where $R_2^1 \equiv \partial R^1/\partial q_2$ and so on. Note that since $R_{11}^1 < 0$, $R_{22}^2 < 0$, and $R_{22}^3 < 0$, the second-order conditions (SOCs) are locally satisfied. The actual values are $\pi_{11}^1 \approx -2.047k$, $\pi_{22}^2 \approx -2.771k$, and $\pi_{33}^3 \approx -2.458k$.

Substitute these results into Eqs. (A.25)–(A.27) to obtain

$$\mathrm{d}q_1/\mathrm{d}q_2 \approx 0.1337, \qquad \mathrm{d}q_1/\mathrm{d}q_3 \approx -0.06048, \tag{A.28}$$

$$\mathrm{d}q_2/\mathrm{d}q_1 \approx 0.04797, \qquad \mathrm{d}q_2/\mathrm{d}q_3 \approx 0.2263, \tag{A.29}$$

$$\mathrm{d}q_3/\mathrm{d}q_1 \approx 0.008132, \qquad \mathrm{d}q_3/\mathrm{d}q_2 \approx -0.006246. \tag{A.30}$$

B Cournot Competition

B.1 Partial derivatives of the revenue functions

The first-order partial derivatives of the revenue functions are as follows:

$$\begin{aligned}
R_1^{c1} &= \frac{(4q_1q_2 + q_1q_3 + 2(q_2)^2)}{4\Phi^3}\left\{16(q_1)^2(q_2)^2 - 8(q_1)^2q_2q_3 - 4q_1(q_2)^3 + (q_1)^2(q_3)^2 + q_1q_3(q_2)^2\right. \\
&\quad \left. +2(q_2)^4\right\} > 0, && \text{(B.1)} \\
R_2^{c1} &= -\frac{(q_1)^2(4q_1q_2 - 2(q_2)^2 - q_1q_3)q_2(2q_2 - q_3)}{\Phi^3} < 0, && \text{(B.2)} \\
R_3^{c1} &= -\frac{(q_1)^2(4q_1q_2 - 2(q_2)^2 - q_1q_3)(q_2)^2}{2\Phi^3} < 0, && \text{(B.3)} \\
R_1^{c2} &= -\frac{q_1(q_2)^3(2q_2 - q_3)^2}{2\Phi^3} < 0, && \text{(B.4)} \\
R_2^{c2} &= \frac{(q_1)^2(2q_2 - q_3)}{4\Phi^3}\left\{8q_1(q_2)^2 - 2q_1q_2q_3 + 2(q_2)^3 + q_1(q_3)^2 - 3(q_2)^2q_3\right\} > 0, && \text{(B.5)} \\
R_3^{c2} &= -\frac{(q_1)^2(q_2)^2(2q_1 - q_2)(2q_2 - q_3)}{2\Phi^3} < 0, && \text{(B.6)} \\
R_1^{c3} &= -\frac{q_1q_3(q_2)^4}{2\Phi^3} < 0, && \text{(B.7)} \\
R_2^{c3} &= \frac{(q_1)^2q_2q_3((q_2)^2 - q_1q_3)}{2\Phi^3}, && \text{(B.8)} \\
R_3^{c3} &= \frac{(q_1)^2(q_2)^2(4q_1q_2 - (q_2)^2 + q_1q_3)}{4\Phi^3} > 0, && \text{(B.9)}
\end{aligned}$$

where $R_2^{c1} \equiv \partial R^{c1}/\partial q_2$ and so on. Only the sign of R_2^{c3} is ambiguous.

The second-order partial derivatives of the revenue functions are as follows:

$$R^{c1}_{11} = -\frac{(4q_2 - q_3)(q_2)^4(4q_1q_2 - 4(q_2)^2 - q_1q_3)}{2\Phi^4}, \tag{B.10}$$

$$R^{c1}_{12} = \frac{q_1(q_2)^3(2q_2 - q_3)(4q_1q_2 - 4(q_2)^2 - q_1q_3)}{\Phi^4}, \tag{B.11}$$

$$R^{c1}_{13} = \frac{q_1(q_2)^4(4q_1q_2 - 4(q_2)^2 - q_1q_3)}{2\Phi^4}, \tag{B.12}$$

$$R^{c2}_{21} = -\frac{q_1(2q_2 - q_3)(q_2)^2}{2\Phi^4}\left\{16q_1(q_2)^2 + 3q_1(q_3)^2 - 10q_2q_1q_3 + 2(q_2)^3 - 3(q_2)^2q_3\right\} < 0, \tag{B.13}$$

$$R^{c2}_{22} = \frac{(q_1)^2}{\Phi^4}\left\{16q_1(q_2)^4 - 2(q_1)^2q_2(q_3)^2 + 8q_1(q_2)^2(q_3)^2 - 16q_1(q_2)^3q_3 - 3q_1(q_2)(q_3)^3 + 2(q_1)^2(q_3)^3 + 2(q_2)^5 - 6(q_2)^4q_3 + 3(q_2)^3(q_3)^2\right\}, \tag{B.14}$$

$$R^{c2}_{23} = -\frac{(q_1)^2q_2(4q_1q_2 - 4q_1q_3 - 4(q_2)^2 + 3q_2q_3)((q_2)^2 - q_1q_3)}{2\Phi^4}, \tag{B.15}$$

$$R^{c3}_{31} = -\frac{q_1(q_2)^4(4q_1q_2 - (q_2)^2 + 2q_1q_3)}{2\Phi^4} < 0, \tag{B.16}$$

$$R^{c3}_{32} = -\frac{(q_1)^2q_2(8(q_1)^2q_2q_3 - 4q_1(q_2)^3 + (q_1)^2(q_3)^2 - 4q_1(q_2)^2q_3 + (q_2)^4)}{2\Phi^4}, \tag{B.17}$$

$$R^{c3}_{33} = \frac{(q_1)^3(q_2)^2(8q_1q_2 + q_1q_3 - 2(q_2)^2)}{2\Phi^4} > 0, \tag{B.18}$$

where $R^{c1}_{12} \equiv \partial^2 R^{c1}/\partial q_1 \partial q_2$ and so on.

B.2 Quality best-response functions

Quality best-response curves in stage 1 are given by the FOCs for firms to maximize profits: $\Pi^1_1 = 0$, $\Pi^2_2 = 0$, and $\Pi^3_3 = 0$. Totally differentiate $\Pi^1_1 = 0$ to obtain the slopes of the quality best-response curve for firm 1 in quality space:

$$\frac{\mathrm{d}q_1}{\mathrm{d}q_2} = -\frac{R^{c1}_{12} + R^{c1}_{13}(\mathrm{d}q_3/\mathrm{d}q_2)}{\Pi^1_{11}}, \tag{B.19}$$

$$\frac{\mathrm{d}q_1}{\mathrm{d}q_3} = -\frac{R^{c1}_{12}(\mathrm{d}q_2/\mathrm{d}q_3) + R^{c1}_{13}}{\Pi^1_{11}}. \tag{B.20}$$

Similarly, totally differentiate $\Pi^2_2 = 0$ to obtain the slopes of the quality best-response curve for firm 2:

$$\frac{\mathrm{d}q_2}{\mathrm{d}q_1} = -\frac{R^{c2}_{21} + R^{c2}_{23}(\mathrm{d}q_3/\mathrm{d}q_1)}{\Pi^2_{22}}, \tag{B.21}$$

$$\frac{\mathrm{d}q_2}{\mathrm{d}q_3} = -\frac{R^{c2}_{21}(\mathrm{d}q_1/\mathrm{d}q_3) + R^{c2}_{23}}{\Pi^2_{22}}. \tag{B.22}$$

Moreover, totally differentiate $\Pi_3^3 = 0$ to obtain the slopes of the quality best-response curve for firm 3:

$$\frac{\mathrm{d}q_3}{\mathrm{d}q_1} = -\frac{R_{31}^{c3} + R_{32}^{c3}(\mathrm{d}q_2/\mathrm{d}q_1)}{\Pi_{33}^3}, \tag{B.23}$$

$$\frac{\mathrm{d}q_3}{\mathrm{d}q_2} = -\frac{R_{31}^{c3}(\mathrm{d}q_1/\mathrm{d}q_2) + R_{32}^{c3}}{\Pi_{33}^3}. \tag{B.24}$$

From (B.19) and (B.24) it yields that

$$\frac{\mathrm{d}q_1}{\mathrm{d}q_2} = \frac{R_{13}^{c1}R_{32}^{c3} - R_{12}^{c1}\Pi_{33}^3}{\Pi_{11}^1\Pi_{33}^3 - R_{13}^{c1}R_{31}^{c3}}, \qquad \frac{\mathrm{d}q_3}{\mathrm{d}q_2} = \frac{R_{31}^{c3}R_{12}^{c1} - R_{32}^{c3}\Pi_{11}^1}{\Pi_{11}^1\Pi_{33}^3 - R_{13}^{c1}R_{31}^{c3}}. \tag{B.25}$$

Similarly, from (B.20) and (B.22) it yields that

$$\frac{\mathrm{d}q_1}{\mathrm{d}q_3} = \frac{R_{12}^{c1}R_{23}^{c2} - R_{13}^{c1}\Pi_{22}^2}{\Pi_{11}^1\Pi_{22}^2 - R_{12}^{c1}R_{21}^{c2}}, \qquad \frac{\mathrm{d}q_2}{\mathrm{d}q_3} = \frac{R_{21}^{c2}R_{13}^{c1} - R_{23}^{c2}\Pi_{11}^1}{\Pi_{11}^1\Pi_{22}^2 - R_{12}^{c1}R_{21}^{c2}}. \tag{B.26}$$

Finally, from (B.21) and (B.23) it yields that

$$\frac{\mathrm{d}q_2}{\mathrm{d}q_1} = \frac{R_{23}^{c2}R_{31}^{c3} - R_{21}^{c2}\Pi_{33}^3}{\Pi_{22}^2\Pi_{33}^3 - R_{23}^{c2}R_{32}^{c3}}, \qquad \frac{\mathrm{d}q_3}{\mathrm{d}q_1} = \frac{R_{32}^{c3}R_{21}^{c2} - R_{31}^{c3}\Pi_{22}^2}{\Pi_{22}^2\Pi_{33}^3 - R_{23}^{c2}R_{32}^{c3}}. \tag{B.27}$$

Under the assumption of $F(q_i) = k(q_i)^2$, where $k > 0$, we can solve the model to obtain product qualities at the unregulated equilibrium: $q_1^* \approx 0.1261/k$, $q_2^* \approx 0.04473/k$, and $q_3^* \approx 0.01305/k$. Substitute these values into Eqs. (B.1)–(B.18) to yield

$$\begin{aligned}
&R_1^{c1} \approx 0.2522, && R_2^{c1} \approx -0.1358, && R_3^{c1} \approx -0.03976,\\
&R_1^{c2} \approx -0.004868, && R_2^{c2} \approx 0.0895, && R_3^{c2} \approx -0.03726,\\
&R_1^{c3} \approx -0.0004866, && R_2^{c3} \approx 0.0002437, && R_3^{c3} \approx 0.02610,\\
&R_{11}^{c1} \approx -0.3349k, && R_{12}^{c1} \approx 0.08698k, && R_{13}^{c1} \approx 0.02546k,\\
&R_{21}^{c2} \approx -0.2610k, && R_{22}^{c2} \approx 0.7385k, && R_{23}^{c2} \approx -0.009607k,\\
&R_{31}^{c3} \approx -0.04702k, && R_{32}^{c3} \approx -0.06289k, && R_{33}^{c3} \approx 0.6701k,
\end{aligned}$$

where $R_2^{c1} \equiv \partial R^{c1}/\partial q_2$ and so on. Note that $R_{11}^{c1} < 0$, but $R_{22}^{c2} > 0$ and $R_{22}^{c3} > 0$. Thus, we assume $F''(q_i)$ is sufficiently large to ensure that the SOCs are locally satisfied. Actually, with $F(q_i) = k(q_i)^2$ it yields that

$$\Pi_{11}^1 \approx -2.03349k < 0, \qquad \Pi_{22}^2 \approx -1.2615k < 0, \qquad \Pi_{33}^3 \approx -1.3299k < 0.$$

Substitute these results into Eqs. (B.25)–(B.27) to obtain

$$\mathrm{d}q_1/\mathrm{d}q_2 \approx 0.04216, \qquad \mathrm{d}q_1/\mathrm{d}q_3 \approx 0.01209, \tag{B.28}$$

$$\mathrm{d}q_2/\mathrm{d}q_1 \approx -0.2067, \qquad \mathrm{d}q_2/\mathrm{d}q_3 \approx -0.01012, \tag{B.29}$$

$$\mathrm{d}q_3/\mathrm{d}q_1 \approx -0.02558, \qquad \mathrm{d}q_3/\mathrm{d}q_2 \approx -0.4878. \tag{B.30}$$

C Policy Coordination

Totally differentiate firms' FOCs under Bertrand competition to yield

$$\begin{pmatrix} \pi^1_{11} & R^1_{12} & R^1_{13} \\ R^2_{21} & \pi^2_{22} & R^2_{23} \\ R^3_{31} & R^3_{32} & \pi^3_{33} \end{pmatrix} \begin{pmatrix} \mathrm{d}q_1 \\ \mathrm{d}q_2 \\ \mathrm{d}q_3 \end{pmatrix} = \begin{pmatrix} F'(q_1) & 0 & 0 \\ 0 & F'(q_2) & 0 \\ 0 & 0 & F'(q_3) \end{pmatrix} \begin{pmatrix} \mathrm{d}s_1 \\ \mathrm{d}s_2 \\ \mathrm{d}s_3 \end{pmatrix}. \tag{C.1}$$

Use Cramer's rule to obtain

$$\frac{\mathrm{d}q_1}{\mathrm{d}s_1} = \frac{F'(q_1)(\pi^2_{22}\pi^3_{33} - R^2_{23}R^3_{32})}{|D|} \qquad \frac{\mathrm{d}q_2}{\mathrm{d}s_1} = -\frac{F'(q_1)(R^2_{21}\pi^3_{33} - R^2_{23}R^3_{31})}{|D|}$$

$$\frac{\mathrm{d}q_3}{\mathrm{d}s_1} = \frac{F'(q_1)(R^2_{21}R^3_{32} - \pi^2_{22}R^3_{31})}{|D|}$$

$$\frac{\mathrm{d}q_1}{\mathrm{d}s_2} = -\frac{F'(q_2)(R^1_{12}\pi^3_{33} - R^1_{13}R^3_{32})}{|D|} \qquad \frac{\mathrm{d}q_2}{\mathrm{d}s_2} = \frac{F'(q_2)(\pi^1_{11}\pi^3_{33} - R^1_{13}R^3_{31})}{|D|}$$

$$\frac{\mathrm{d}q_3}{\mathrm{d}s_2} = -\frac{F'(q_2)(\pi^1_{11}R^3_{32} - R^1_{12}R^3_{31})}{|D|}$$

$$\frac{\mathrm{d}q_1}{\mathrm{d}s_3} = \frac{F'(q_3)(R^1_{12}R^2_{23} - R^1_{13}\pi^2_{22})}{|D|} \qquad \frac{\mathrm{d}q_2}{\mathrm{d}s_3} = -\frac{F'(q_3)(\pi^1_{11}R^2_{23} - R^1_{13}R^2_{21})}{|D|}$$

$$\frac{\mathrm{d}q_3}{\mathrm{d}s_3} = \frac{F'(q_3)(\pi^1_{11}\pi^2_{22} - R^1_{12}R^2_{21})}{|D|},$$

where $|D|$ is the determinant of the matrix on the left-hand side in Eq. (C.1).

Corresponding expressions in the case of Cournot competition are obtained by replacing R^i by R^{ci} and π^i by Π^i.

Similarly, in the subsections below, we only present the results in the case of Bertrand competition. Corresponding results in the case of Cournot competition are obtained by replacing R^i by R^{ci} and π^i by Π^i.

C.1 Policy Coordination by Countries 1 and 2

In this case, the governments of Countries 1 and 2 choose s_1 and s_2 to maximize their joint welfare $W^1 + W^2$. The FOCs yield

$$\hat{s}_1^{12} = \frac{1}{F'(q_1)} \left\{ R_1^2 + (R_3^1 + R_3^2)\Theta \right\} \tag{C.2}$$

$$\hat{s}_2^{12} = \frac{1}{F'(q_2)} \left[R_2^1 + \frac{R_3^1 + R_3^2}{R_{23}^2 R_{31}^3 - R_{21}^2 \pi_{33}^3} \left\{ (R_{21}^2 R_{32}^3 - \pi_{22}^2 R_{31}^3) - \Theta(\pi_{22}^2 \pi_{33}^3 - R_{23}^2 R_{32}^3) \right\} \right], \tag{C.3}$$

where the superscript of $\hat{s}_i$ indicates which countries coordinate their policy and

$$\begin{aligned} \Theta &= \frac{(\mathrm{d}q_2/\mathrm{d}s_2)(\mathrm{d}q_3/\mathrm{d}s_1) - (\mathrm{d}q_2/\mathrm{d}s_1)(\mathrm{d}q_3/\mathrm{d}s_2)}{(\mathrm{d}q_2/\mathrm{d}s_2)(\mathrm{d}q_1/\mathrm{d}s_1) - (\mathrm{d}q_2/\mathrm{d}s_1)(\mathrm{d}q_1/\mathrm{d}s_2)} \\ &= \frac{(\pi_{11}^1 \pi_{33}^3 - R_{13}^1 R_{31}^3)(R_{21}^2 R_{32}^3 - \pi_{22}^2 R_{31}^3) + (R_{21}^2 \pi_{33}^3 - R_{23}^2 R_{31}^3)(R_{12}^1 R_{31}^3 - \pi_{11}^1 R_{32}^3)}{(\pi_{11}^1 \pi_{33}^3 - R_{13}^1 R_{31}^3)(\pi_{22}^2 \pi_{33}^3 - R_{23}^2 R_{32}^3) + (R_{21}^2 \pi_{33}^3 - R_{23}^2 R_{31}^3)(R_{13}^1 R_{32}^3 - R_{12}^1 \pi_{33}^3)}. \end{aligned}$$

The signs of $\hat{s}_1^{12}$ and $\hat{s}_2^{12}$ are generally ambiguous. We use the result obtained by assuming $F(q_i) = k(q_i)^2$ to evaluate the values of $\hat{s}_1^{12}$ and $\hat{s}_2^{12}$ at the unregulated equilibrium:

Bertrand: $\hat{s}_1^{12} = 0.001254 > 0$, $\hat{s}_2^{12} = -3.084 < 0$.

Cournot: $\hat{s}_1^{c12} = -0.008505 < 0$, $\hat{s}_2^{c12} = -1.478 < 0$.

C.2 Policy Coordination by Countries 1 and 3

In this case, the governments of Countries 1 and 3 choose s_1 and s_3 to maximize their joint welfare $W^1 + W^3$. The FOCs yield

$$\hat{s}_1^{13} = \frac{1}{F'(q_1)} \left\{ R_1^3 + (R_2^1 + R_2^3)\Lambda \right\} \tag{C.4}$$

$$\hat{s}_3^{13} = \frac{1}{F'(q_3)} \left[R_3^1 + \frac{R_2^1 + R_2^3}{R_{21}^2 R_{32}^3 - \pi_{22}^2 R_{31}^3} \left\{ (R_{23}^2 R_{31}^3 - R_{21}^2 \pi_{33}^3) - \Lambda(\pi_{22}^2 \pi_{33}^3 - R_{23}^2 R_{32}^3) \right\} \right], \tag{C.5}$$

where

$$\begin{aligned} \Lambda &= \frac{(\mathrm{d}q_3/\mathrm{d}s_3)(\mathrm{d}q_2/\mathrm{d}s_1) - (\mathrm{d}q_3/\mathrm{d}s_1)(\mathrm{d}q_2/\mathrm{d}s_3)}{(\mathrm{d}q_3/\mathrm{d}s_3)(\mathrm{d}q_1/\mathrm{d}s_1) - (\mathrm{d}q_3/\mathrm{d}s_1)(\mathrm{d}q_1/\mathrm{d}s_3)} \\ &= \frac{(\pi_{11}^1 \pi_{22}^2 - R_{12}^1 R_{21}^2)(R_{23}^2 R_{31}^3 - R_{21}^2 \pi_{33}^3) - (R_{21}^2 R_{32}^3 - \pi_{22}^2 R_{31}^3)(R_{13}^1 R_{21}^2 - \pi_{11}^1 R_{23}^2)}{(\pi_{11}^1 \pi_{22}^2 - R_{12}^1 R_{21}^2)(\pi_{22}^2 \pi_{33}^3 - R_{23}^2 R_{32}^3) - (R_{21}^2 R_{32}^3 - \pi_{22}^2 R_{31}^3)(R_{12}^1 R_{23}^2 - R_{13}^1 \pi_{22}^2)}. \end{aligned}$$

The signs of $\hat{s}_1^{13}$ and $\hat{s}_3^{13}$ are generally ambiguous. We use the result obtained by assuming $F(q_i) =$

$k(q_i)^2$ to evaluate the values of $\hat{s}_1^{13}$ and $\hat{s}_3^{13}$ at the unregulated equilibrium:

$$\text{Bertrand:} \quad \hat{s}_1^{13} = -0.002770 < 0, \qquad \hat{s}_3^{13} = -12.20 < 0.$$

$$\text{Cournot:} \quad \hat{s}_1^{c13} = 0.1093 > 0, \qquad \hat{s}_3^{c13} = -1.484 < 0.$$

C.3 Policy Coordination by Countries 2 and 3

In this case, the governments of Countries 2 and 3 choose s_2 and s_3 to maximize their joint welfare $W^2 + W^3$. The FOCs yield

$$\hat{s}_2^{23} = \frac{1}{F'(q_2)} \left\{ R_2^3 + (R_1^2 + R_1^3)\Gamma \right\} \tag{C.6}$$

$$\hat{s}_3^{23} = \frac{1}{F'(q_3)} \left[R_3^2 + \frac{R_1^2 + R_1^3}{R_{12}^1 R_{31}^3 - \pi_{11}^1 R_{32}^3} \left\{ (R_{13}^1 R_{32}^3 - R_{12}^1 \pi_{33}^3) - \Gamma(\pi_{11}^1 \pi_{33}^3 - R_{13}^1 R_{31}^3) \right\} \right], \tag{C.7}$$

where

$$\begin{aligned}
\Gamma &= \frac{(\mathrm{d}q_3/\mathrm{d}s_3)(\mathrm{d}q_1/\mathrm{d}s_2) - (\mathrm{d}q_1/\mathrm{d}s_3)(\mathrm{d}q_3/\mathrm{d}s_2)}{(\mathrm{d}q_3/\mathrm{d}s_3)(\mathrm{d}q_2/\mathrm{d}s_2) - (\mathrm{d}q_2/\mathrm{d}s_3)(\mathrm{d}q_3/\mathrm{d}s_2)} \\
&= \frac{(\pi_{11}^1 \pi_{22}^2 - R_{12}^1 R_{21}^2)(R_{13}^1 R_{32}^3 - R_{12}^1 \pi_{33}^3) - (R_{12}^1 R_{23}^2 - R_{13}^1 \pi_{22}^2)(R_{12}^1 R_{31}^3 - \pi_{11}^1 R_{32}^3)}{(\pi_{11}^1 \pi_{22}^2 - R_{12}^1 R_{21}^2)(\pi_{11}^1 \pi_{33}^3 - R_{13}^1 R_{31}^3) - (R_{13}^1 R_{21}^2 - \pi_{11}^1 R_{23}^2)(R_{12}^1 R_{31}^3 - \pi_{11}^1 R_{32}^3)}.
\end{aligned}$$

The signs of $\hat{s}_2^{23}$ and $\hat{s}_3^{23}$ are generally ambiguous. We use the result obtained by assuming $F(q_i) = k(q_i)^2$ to evaluate the values of $\hat{s}_2^{23}$ and $\hat{s}_3^{23}$ at the unregulated equilibrium:

$$\text{Bertrand:} \quad \hat{s}_2^{23} = -0.006266 < 0, \qquad \hat{s}_3^{23} = -3.439 < 0.$$

$$\text{Cournot:} \quad \hat{s}_2^{c23} = 0.0001643 > 0, \qquad \hat{s}_3^{c23} = -1.430 < 0.$$

C.4 Policy Coordination by All Exporting Countries

In this case, the governments of Countries 1, 2, and 3 choose s_1, s_2, and s_3 to maximize their joint welfare $W^1 + W^2 + W^3$. The FOCs yield

$$\hat{s}_1^{123} = \frac{R_1^2 + R_1^3}{F'(q_1)} \tag{C.8}$$

$$\hat{s}_2^{123} = \frac{R_2^1 + R_2^3}{F'(q_2)} \tag{C.9}$$

$$\hat{s}_3^{123} = \frac{R_3^1 + R_3^2}{F'(q_3)}. \tag{C.10}$$

Under Bertrand competition, from Eqs. (A.2)–(A.4) and Eqs. (A.6)–(A.7) we know that $R_2^1 < 0$, $R_3^1 < 0$, $R_1^2 > 0$, $R_3^2 < 0$, and $R_1^3 > 0$. Thus, $\hat{s}_1^{123} > 0$ and $\hat{s}_3^{123} < 0$. The sign of $\hat{s}_2^{123}$ is ambiguous. By assuming $F(q_i) = k(q_i)^2$, we have $R_2^3 < 0$ and hence $\hat{s}_2^{123} < 0$.

Under Cournot competition, from Eqs. (B.2)–(B.4) and Eqs. (B.6)–(B.7) we know that $R_2^{c1} < 0$, $R_3^{c1} < 0$, $R_1^{c2} < 0$, $R_3^{c2} < 0$, and $R_1^{c3} < 0$. Thus, $\hat{s}_1^{c123} < 0$ and $\hat{s}_3^{c123} < 0$. The sign of $\hat{s}_2^{c123}$ is ambiguous. By assuming $F(q_i) = k(q_i)^2$, we have $R_2^{c3} > 0$. Since R_2^{c1} dominates R_2^{c3}, we have $\hat{s}_2^{c123} < 0$.

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