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RESEARCH ARTICLE

International R&D Rivalry with Spillovers and Tariff Policies

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Abstract This paper investigates the effects of R&D spillovers on the R&D choices of foreign exporters when the importing country adopts either uniform or discriminatory alternative tariff regimes. We show that the importing country should optimally choose a uniform tariff regime. A uniform tariff regime is also advantageous for foreign exporters if the R&D spillovers are sufficiently large. A comparison of free trade with the two tariff regimes reveals that there are some situations in which both the importing country and foreign exporters are better off under free trade, which supports trade liberalization.

Keywords R&D spillovers · Uniform tariffs · Discriminatory tariffs · Free trade

JEL Classification F13 · L13

1 Introduction

This paper investigates the effects of R&D spillovers on the R&D choices of foreign exporters in the presence of tariffs imposed by the importing country. It uses trade literature on tariff policies and industrial organization literature on R&D choices in an analysis of how the welfare of the importing country and the profits of the exporting firms are affected by R&D spillovers, R&D investments, and the tariff policies.

Our analysis is built upon two existing sets of literature. One set is related to optimal tariff policies, mainly analyzing the choice between a uniform tariff regime, as required by the "most favored nation" (MFN) clause of the WTO, and a discriminatory tariff regime, and the welfare effects of the tariff regime in a model with two foreign exporting firms competing in a third country. Assuming that the cost structures of the exporters are given exogenously, Gatsios (1990) and Hwang

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and Mai (1991) show that the importing country benefits most by imposing higher tariffs on exporters who are more cost efficient. Choi (1995) extends the literature by endogenizing the technology choices of the exporters, and shows that technology with a higher (lower) marginal cost is adopted by the exporters under a discriminatory (uniform) tariff regime. Horiba and Tsutsui (2000) examine the effect of the tariff regime on the long-run capacity decisions of the exporters. They find that firms would choose smaller plant sizes and lower levels of output under a discriminatory tariff regime. Liao and Wong (2006) show that under a discriminatory tariff regime, the optimal export subsidy for an exporting country may be negative (i.e., an export tax). Moreover, Choi (1995), Horiba and Tsutsui (2000), and Liao and Wong (2006) all show that the importing country is better off under a uniform tariff regime.

The second set of relevant literature is related to R&D competition/cooperation with spillovers, mainly focused on how R&D efforts are affected by the R&D spillover effect. In a seminal paper, d'Aspremont and Jacquemin (1988) show that cooperative R&D levels exceed noncooperative R&D levels when the degree of spillovers exceeds 0.5, and vice versa. Many subsequent papers have adopted their framework, with modifications.[1] The increasing number of agreements on international R&D cooperation and research joint ventures has led to the R&D spillover effect being addressed more widely in an international context.

In this paper, we extend the work of Choi (1995) by incorporating R&D spillovers into our model. In effect, the model of Choi corresponds to the special case of a zero degree of spillovers in our model. We analyze the welfare and profit impacts of two tariff regimes: uniform and discriminatory. Choosing between these two tariff regimes is an interesting issue in the present framework, because it not only determines the welfare of the importing country, but also affects the investment in and profit from R&D for a firm. Moreover, we extend Choi (1995) by comparing free trade with the two tariff regimes in terms of the welfare of the importing country and the profits of the exporting firms.

The argument of Choi (1995) is still applicable in the presence of some degree of R&D spillovers: as long as the spillover effect is not completely perfect, the exporting firms invest less (more) in R&D so that their effective marginal costs are higher (lower) under a discriminatory (uniform) tariff regime. Moreover, the importing country prefers a uniform tariff regime when the spillover is not completely perfect, but otherwise is indifferent to the regime.

The most striking result of this paper is that both exporting firms prefer a uniform tariff regime when the degree of R&D spillovers is sufficiently high.[2] When spillovers are substantial, the two firms underinvest in R&D when they act noncooperatively, and the noncooperative R&D level is smaller than the cooperative R&D level. Thus, a small increase in R&D increases the profits of the firms. Since the firms invest more under a uniform tariff regime than under a discriminatory tariff regime, they are better off under the former. In such a case, the importing country and the exporting firms all prefer a uniform tariff regime.

[1] For extensive literature surveys, see DeBondt (1996), Veugelers (1998), and Kaiser (2002a).

[2] Choi (1995), Horiba and Tsutsui (2000), and Liao and Wong (2006) all show that when the demand is linear, the exporting firms (or countries) are better off under a discriminatory tariff regime.

Comparing free trade with the two tariff regimes, we find some conditions under which the importing country can benefit from an ex ante commitment to free trade due to its positive effects on R&D. This result suggests that the preconception that unilateral trade activism generally improves welfare does not hold in the present model. Moreover, we find that exporting firms may prefer discriminatory tariffs to free trade. This is because the firms overinvest in R&D even more under free trade, and the loss in profit due to overproduction outweighs the savings in tariff payments. Finally, we identify conditions under which the importing country and the exporting firms are all better off under free trade, supporting the argument for the WTO to promote trade liberalization.

It is worth relating this paper to the work of Saggi and Yildiz (2005) who, in a comparison of the welfare effects of MFN and tariff discrimination in an oligopoly model, found that the MFN clause does not always dominate tariff discrimination from a worldwide welfare perspective when the exporting countries are asymmetric in both cost and market structures. Although they also compare the welfare effects of MFN and tariff discrimination, the models and the issues they addressed differ from ours.

The remainder of the paper is organized as follows: Section 2 describes the model and the four-stage game, and analyzes the equilibrium R&D levels under a discriminatory tariff regime and a uniform tariff regime. Section 3 compares the effects of the two tariff regimes on the welfare of the importing country and the profits of the exporting firms. Section 4 compares free trade with the two tariff regimes, and Section 5 provides a brief summary and some concluding remarks.

2 The model

2.1 Assumptions

We consider a one-product, two-firm, three-country model as used by Choi (1995). Two of the countries, which are numbered 1 and 2, each have a firm that produces a homogeneous product to be exported to the third country, M.[3] Demand in country M is given by an inverse demand function, $p=p(Q)$, where p is the market price. We assume that $p(.)$ is decreasing and is twice continuously differentiable, with $p''(Q)Q+p'(Q)<0$. The output of firm i (the one in country i) is denoted by q_i, $i=1,2$, and $Q=q_1+q_2$ in equilibrium. Initially, firm i has a constant marginal cost c_i, which is independent of the production level. Each firm is able to lower its marginal cost through R&D investment x_i. Following d'Aspremont and Jacquemin (1988) and most of the literature, we assume that the R&D production function is linear. The R&D investment is subject to diminishing returns, as captured by the quadratic form of the R&D cost, $\gamma x_i^2/2$, $\gamma>0$. The R&D of firm i not only leads to a reduction in its own marginal cost, but also spills over to firm j, $i,j=1,2$ and $i\neq j$. We define $\beta\in[0,1]$ as the degree of R&D spillovers, which represents the proportion of the cost

[3] Although the model of "competition in the third market"—as described by Choi (1995) and others—is quite restrictive, we use this model for simplicity, which also allows our results to be directly compared with those of Choi (1995).

reduction of firm i that enters additively and costlessly into the marginal cost reduction of firm j. Thus, through its own R&D and the spillovers of the R&D of firm j, the marginal cost of firm i becomes $MC_i = c_i - x_i - \beta x_j$.[4]

We consider the following four-stage, one-shot noncooperative game. In the first stage, country M announces whether it is using a uniform tariff regime or a discriminatory tariff regime. In the second stage, the two firms choose their respective R&D levels, x_1 and x_2, simultaneously and noncooperatively. In the third stage, country M imposes tariffs according to the tariff regime it announced in the first stage. In the fourth stage, the two firms compete in quantities in the market of country M. Note that country M is assumed to choose the tariff regime before, but the actual tariff rates after, the firms have chosen their R&D investments. This reflects the R&D choice generally being irreversible and it being easy for the importing country to set its tariff rate, while the tariff regime, which represents the country's international commitment or position in an international setting (e.g., whether it has to follow the MFN clause of the GATT/WTO), is more difficult to change.

In the following we analyze the two tariff regimes separately, and then compare them in terms of the welfare of the importing country and the profits of the two exporting firms.

2.2 R&D competition under a discriminatory tariff regime

We denote the specific import tariff imposed by country M on the product from country i by t_i, i=1,2. The game is solved by backward induction. In the fourth stage, the maximization problem for firm i is given by

$$\max_{q_i} \pi_i = \left[p(Q) - c_i + x_i + \beta x_j - t_i\right] q_i - \frac{1}{2}\gamma x_i^2, i,j = 1,2, \text{and } i \neq j,$$

and the first-order condition is given by[5]

$$\frac{\partial \pi_i}{\partial q_i} = p' q_i + p - c_i + x_i + \beta x_j - t_i = 0, i,j = 1,2, \text{and } i \neq j. \quad (1)$$

The two first-order conditions in Eq. 1 can be solved simultaneously to obtain the equilibrium outputs $q_1^*(x_1, x_2, t_1, t_2)$ and $q_2^*(x_1, x_2, t_1, t_2)$. The comparative statics results show that an increase in tariff on firm i will reduce q_i^* and the total output, but increase q_j^*. Besides, the R&D performed by firm i increases its own output q_i^* and the total output, but the effect of this on q_j^* depends on the magnitude of β: if β is large (small), an increase in x_i leads to large (small) q_j^*.

[4] Following the traditional models such as those of d'Aspremont and Jacquemin (1988) and Kamien et al. (1992), we assume that absorptive capacity is independent of one's own R&D efforts. Therefore, firm i can benefit from the R&D efforts of firm j even if it does not itself invest in R&D. For theoretical models that include the effects of absorptive capacity, see Cohen and Levinthal (1989), Kamien and Zang (2000), Campisi et al. (2001), Kaiser (2002b), Martin (2002), and Grűnfeld (2003).

[5] The second-order condition $p'' q_i + 2p' < 0$ and the stability condition $\Delta_1 \equiv p' p'' Q + 3(p')^2 > 0$ are satisfied.

In the third stage, country M sets tariffs t_1 and t_2 so as to maximize its national welfare, which is defined as the sum of consumer surplus and tariff revenue: $W_M^d(x_1, x_2, t_1, t_2) = \int_0^{Q^*} p(x)dx - p\left(Q^*\right)Q^* + t_1 q_1^* + t_2 q_2^*$. The first-order conditions for maximization are given by[6]

$$\frac{\partial W_M^d}{\partial t_i} = -p'Q^* \frac{\partial Q^*}{\partial t_i} + q_i^* + t_1 \frac{\partial q_1^*}{\partial t_i} + t_2 \frac{\partial q_2^*}{\partial t_i} = 0, i = 1, 2. \tag{2}$$

Solving the two conditions in Eq. 2 simultaneously yields the optimal discriminatory tariffs:

$$t_i^* = -p'q_i^* - p''\left[(q_1^*)^2 + (q_2^*)^2\right], i = 1, 2.$$

By using Eq. 1, the difference between the two tariff rates is equal to

$$t_i^* - t_j^* = p'\left(q_j^* - q_i^*\right) = \frac{1}{2}\left[\left(c_j - x_j - \beta x_i\right) - \left(c_i - x_i - \beta x_j\right)\right], \quad i,j = 1, 2, \text{ and } i \neq j. \tag{3}$$

Equation 3 is just the 50% rule of Hwang and Mai (1991): the difference between the optimal tariffs chosen by country M equals half the difference of the effective marginal costs. Differentiating both sides of Eq. 3 with respect to x_i yields

$$\frac{\partial\left(t_i^* - t_j^*\right)}{\partial x_i} = \frac{1}{2}(1 - \beta) \geq 0. \tag{4}$$

Equation 4 shows that when $\beta \neq 1$, an increase in the R&D of firm i leads to an increase in the tariff-rate differential. It also shows that $\partial t_i^*/\partial x_i > \partial t_j^*/\partial x_i$, implying that the R&D of firm i has a greater adverse effect on its own tariff than on that of its rival. When $\beta = 1$, the tariff-rate differential always equals $\left(c_j - c_i\right)/2$ irrespective of the levels of x_1 and x_2, so the R&D level of either firm does not affect the tariff-rate differential.

In the second stage, firm i chooses the R&D level that will maximize its profit, and the first-order condition is given by[7]

$$\frac{\partial \pi_i^d}{\partial x_i} = q_i^*\left[1 - \frac{\partial t_i^*}{\partial x_i} + p'\left(\frac{\partial q_j^*}{\partial t_i}\frac{\partial t_i^*}{\partial x_i} + \frac{\partial q_j^*}{\partial t_j}\frac{\partial t_j^*}{\partial x_i} + \frac{\partial q_j^*}{\partial x_i}\right)\right] - \gamma x_i = 0, i,j = 1, 2, \text{ and } i \neq j. \tag{5}$$

Solving the two first-order conditions in Eq. 5 simultaneously yields the noncooperative equilibrium R&D levels x_1^d and x_2^d.

[6] The second-order conditions, $g_{11}<0$ and $g_{22}<0$, and the stability condition $\Delta_2 \equiv g_{11}g_{22} - g_{12}g_{21} > 0$ are assumed, where $g_{ij} = \partial^2 W_M^d/\partial t_i \partial t_j, i,j = 1, 2$.

[7] The second-order and stability conditions are assumed so as to ensure global uniqueness of the Nash equilibrium in the game. For a linear-demand case, the second-order condition is $32b\gamma - (3 - \beta)^2 > 0$ and the stability condition requires $|(3 - \beta)(3\beta - 1)/[32b\gamma - (3 - \beta)^2]| < 1$. For a general demand function, the second-order and stability conditions are satisfied if $b\gamma$ is sufficiently large.

2.3 R&D competition under a uniform tariff regime

We now examine the Nash equilibrium R&D level when country M announces the adoption of a uniform tariff regime in the first stage. We denote the uniform specific tariff imposed by country M by $\hat{t}$. In the fourth stage, firm i chooses the output that will maximize its profit. The first-order condition is given by

$$\frac{\partial \pi_i}{\partial q_i} = p' q_i + p - c_i + x_i + \beta x_j - \hat{t} = 0, i, j = 1, 2, \text{ and } i \neq j. \tag{6}$$

The two first-order conditions in Eq. 6 can be solved simultaneously to obtain the equilibrium outputs $q_1^*\left(x_1, x_2, \hat{t}\right)$ and $q_2^*\left(x_1, x_2, \hat{t}\right)$.

In the third stage, country M chooses $\hat{t}$ to maximize its national welfare: $W_M^u\left(x_1, x_2, \hat{t}\right) = \int_0^{Q^*} p(x)\mathrm{d}x - p(Q^*)Q^* + \hat{t}Q^*$. The first-order condition for maximization is given by

$$\frac{\partial W_M^u}{\partial \hat{t}} = -p' Q^* \frac{\partial Q^*}{\partial \hat{t}} + Q^* + \hat{t}\frac{\partial Q^*}{\partial \hat{t}} = 0. \tag{7}$$

The solution to the first-order condition (7) is $\hat{t}^* = -(p'' Q^* + p')Q^*/2 > 0$.

In the second stage, firm i chooses the R&D level that will maximize its profit, and the first-order condition is given by[8]

$$\frac{\partial \pi_i^u}{\partial x_i} = q_i^* \left[1 - \frac{\partial \hat{t}^*}{\partial x_i} + p' \left(\frac{\partial q_j^*}{\partial \hat{t}} \frac{\partial \hat{t}^*}{\partial x_i} + \frac{\partial q_j^*}{\partial x_i}\right)\right] - \gamma x_i = 0, i, j = 1, 2, \text{ and } i \neq j. \tag{8}$$

Solving the two first-order conditions in Eq. 8 simultaneously yields the noncooperative equilibrium R&D levels x_1^u and x_2^u.

Since $\left(x_1^d, x_2^d\right)$ and $\left(x_1^u, x_2^u\right)$ depend on the initial costs of the firms, (c_1, c_2), analyzing the effect of the initial technology used by a firm on its R&D choice yields the following proposition:

Proposition 1 *If $p'' \geq 0$, the firm with a lower initial marginal cost will invest more in R&D. If the two firms are identical with the same initial marginal cost, they always choose the same R&D level.*

Proof Consider a discriminatory tariff regime. Without loss of generality, we assume $c_1 < c_2$. To compare x_1^d and x_2^d, evaluate $\partial \pi_1^d / \partial x_1$ at $x_1 = x_2 = x_2^d$. Define $\delta = q_1^*\left(x_2^d, x_2^d, t_1^*, t_2^*\right) - q_2^*\left(x_2^d, x_2^d, t_1^*, t_2^*\right)$, and from Eqs. 1 and 3 we know $\delta > 0$. Let $\eta_i = 1 - (\partial t_i^*/\partial x_i) + p'\left[(\partial q_j^*/\partial t_i)(\partial t_i^*/\partial x_i) + (\partial q_j^*/\partial t_j)(\partial t_j^*/\partial x_i) + (\partial q_j^*/\partial x_i)\right]$. Assuming symmetry such that $\partial t_1^*/\partial x_1 = \partial t_2^*/\partial x_2$ and $\partial t_1^*/\partial x_2 = \partial t_2^*/\partial x_1$ yields

$$\begin{aligned} \left.\frac{\partial \pi_1^d}{\partial x_1}\right|_{x_1 = x_2 = x_2^d} &= q_1^*\left(x_2^d, x_2^d, t_1^*, t_2^*\right)\eta_1 - q_2^*\left(x_2^d, x_2^d, t_1^*, t_2^*\right)\eta_2 \\ &= q_2^*(\eta_1 - \eta_2) + \delta\eta_1 \\ &= \frac{q_2^* p' p'' \delta}{\Delta_1}\left[\frac{\partial t_1^*}{\partial x_1} + \frac{\partial t_2^*}{\partial x_1} - (1+\beta)\right] + \delta\eta_1. \end{aligned}$$

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[8] For a linear-demand case, the second-order condition is $32b\gamma - (5 - 3\beta)^2 < 0$ and the stability condition requires $\left|(5 - 3\beta)(5\beta - 3)\Big/\left[32b\gamma - (5 - 3\beta)^2\right]\right| < 1$. For a general demand function, the second-order and stability conditions are satisfied if $b\gamma$ is sufficiently large.

Totally differentiating Eq. 2 with respect to x_1 yields

$$\begin{bmatrix} g_{11} & g_{12} \\ g_{21} & g_{22} \end{bmatrix} \begin{bmatrix} \partial t_1^*/\partial x_1 \\ \partial t_2^*/\partial x_1 \end{bmatrix} = \begin{bmatrix} -\partial^2 W_M^d/\partial t_1 \partial x_1 \\ -\partial^2 W_M^d/\partial t_2 \partial x_1 \end{bmatrix} = \begin{bmatrix} (g_{11} - \partial q_1^*/\partial t_1) + \beta(g_{21} - \partial q_2^*/\partial t_1) \\ (g_{12} - \partial q_1^*/\partial t_2) + \beta(g_{22} - \partial q_2^*/\partial t_2) \end{bmatrix}. \tag{9}$$

Solving Eq. 9 and assuming symmetry such that $g_{11}=g_{22}$ yields

$$\frac{\partial t_1^*}{\partial x_1} + \frac{\partial t_2^*}{\partial x_1} = \frac{1}{\Delta_2}\left[(1+\beta)\Delta_2 + (g_{12} - g_{11})\left(\frac{\partial q_1^*}{\partial t_1} + \frac{\partial q_1^*}{\partial t_2} + \beta\left(\frac{\partial q_2^*}{\partial t_2} + \frac{\partial q_2^*}{\partial t_1}\right)\right)\right] < 1+\beta, \tag{10}$$

because $g_{12} - g_{11} > 0$ and $\partial q_i^*/\partial t_i + \partial q_i^*/\partial t_j < 0$. Since $\delta>0$, $\eta_1>0$, and $\partial t_1^*/\partial x_1 + \partial t_2^*/\partial x_1 < 1+\beta$, $\partial \pi_1^d/\partial x_1|_{x_1=x_2=x_2^d} > 0$ if $p'' \geq 0$. Thus, if $p'' \geq 0$, $\partial \pi_1^d/\partial x_1|_{x_1=x_2=x_2^d} > 0$, implying that $x_1^d > x_2^d$. If $c_1=c_2$, then $\delta=0$ and it is obvious that $\partial \pi_1^d/\partial x_1|_{x_1=x_2=x_2^d} = 0$, implying that $x_1^d = x_2^d$.

The proof for the case under a uniform tariff regime is analogous, and hence is omitted. ■

Gatsios (1990) and Hwang and Mai (1991) show that the discriminatory tariff regime favors the high-cost firm, since the importing country imposes a lower tariff on it. Choi (1995) further shows that the discriminatory tariff regime discourages firms to adopt technology with a lower marginal cost. Despite the discriminatory tariff regime favoring the high-cost firm, Proposition 1 shows that taking into account the impact of the R&D on the tariffs and the outputs, the initially low-cost firm will still invest more in R&D to reduce its marginal cost even further.

3 Uniform or discriminatory tariffs?

In this section we examine the impacts of the two tariff regimes on the welfare of country M and the profits of the two exporting firms. To simplify the analysis, we consider a symmetric case in which $c_1=c_2$,[9] for which Proposition 1 shows that the two firms will choose the same R&D level. Therefore, from Eq. 3 we know that the optimal discriminatory tariffs imposed on the two firms will be the same. We have the following lemma:

Lemma 1 *Suppose that the two firms are identical with the same initial marginal cost. If the R&D spillover effect is not completely perfect, that is, $\beta \neq 1$, the firms will invest more in R&D under a uniform tariff regime than under a discriminatory tariff regime. If $\beta = 1$, the R&D level chosen under the two tariff regimes will be the same.*

Proof Denote the common, noncooperative R&D levels as x^d and x^u under discriminatory and uniform tariff regimes, respectively. To compare x^d and x^u,

[9] This assumption eliminates the effects of the firms having different initial technologies on the R&D choices, as shown in Proposition 1, thereby concentrating more on the effects of the tariff regimes on the R&D choices.

evaluate $\partial\pi_i^d/\partial x_i$ at $x_1{=}x_2{=}x^u$. With the assumption that $c_1{=}c_2$, $t_1^*(x,x) = t_2^*(x,x) = \hat{t}^*(x,x)$ and $q_i^*\left(x^u,x^u,t_1^*,t_2^*\right) = q_i^*\left(x^u,x^u,\hat{t}^*\right)$. We have

$$\begin{aligned}
\left.\frac{\partial\pi_i^d}{\partial x_i}\right|_{x_1=x_2=x^u} &= q_i^*(x^u,x^u,t_1^*,t_2^*)\eta_i - q_i^*\left(x^u,x^u,\hat{t}^*\right)\left[1-\frac{\partial\hat{t}^*}{\partial x_i}+p'\left(\frac{\partial q_j^*}{\partial\hat{t}}\frac{\partial\hat{t}^*}{\partial x_i}+\frac{\partial q_j^*}{\partial x_i}\right)\right] \\
&= q_i^*\left[\frac{\partial\hat{t}^*}{\partial x_i}-\frac{\partial t_i^*}{\partial x_i}+p'\left(\frac{\partial q_j^*}{\partial t_i}\frac{\partial t_i^*}{\partial x_i}+\frac{\partial q_j^*}{\partial t_j}\frac{\partial t_j^*}{\partial x_i}-\frac{\partial q_j^*}{\partial\hat{t}}\frac{\partial\hat{t}^*}{\partial x_i}\right)\right] \\
&= q_i^*\left[\frac{\partial\hat{t}^*}{\partial x_i}-\frac{\partial t_i^*}{\partial x_i}+p'\left(\frac{\partial q_j^*}{\partial t_i}\frac{\partial t_i^*}{\partial x_i}+\frac{\partial q_j^*}{\partial t_j}\left(\frac{\partial t_i^*}{\partial x_i}-\frac{1-\beta}{2}\right)-\frac{\partial q_j^*}{\partial\hat{t}}\frac{\partial\hat{t}^*}{\partial x_i}\right)\right] \\
&= q_i^*\left[\frac{\partial\hat{t}^*}{\partial x_i}-\frac{\partial t_i^*}{\partial x_i}+\frac{(p')^2}{\Delta_1}\left(\frac{\partial t_i^*}{\partial x_i}-\frac{\partial\hat{t}^*}{\partial x_i}\right)-\frac{p'(1-\beta)}{2}\frac{\partial q_j^*}{\partial t_j}\right] \\
&= q_i^*\left[-\left(\frac{\partial t_i^*}{\partial x_i}-\frac{\partial\hat{t}^*}{\partial x_i}\right)\left(\frac{p''Q+2p'}{p''Q+3p'}\right)-\frac{p'(1-\beta)}{2}\frac{\partial q_j^*}{\partial t_j}\right]\le 0,
\end{aligned}$$

because $\partial t_i^*/\partial x_i \ge \partial\hat{t}^*/\partial x_i$, where the equality holds when $\beta{=}1$. To show $\partial t_i^*/\partial x_i \ge \partial\hat{t}^*/\partial x_i$, we first prove that $\partial t_i^*/\partial x_i + \partial t_j^*/\partial x_i = 2\left(\partial\hat{t}^*/\partial x_i\right)$. With the assumption of identical firms, from Eq. 10 we have

$$\frac{\partial t_i^*}{\partial x_i}+\frac{\partial t_j^*}{\partial x_i}=\frac{(1+\beta)}{\Delta_2}\left[\Delta_2+\left(\frac{\partial q_i^*}{\partial t_i}+\frac{\partial q_i^*}{\partial t_j}\right)(g_{ij}-g_{ii})\right]=(1+\beta)\left[1-\frac{p'}{\Delta_1\left(g_{ii}+g_{ij}\right)}\right]. \tag{11}$$

On the other hand, differentiating W_M^u with respect to x_i yields

$$\frac{\partial W_M^u}{\partial x_i}=-p'Q^*\frac{\partial Q^*}{\partial x_i}+\hat{t}\frac{\partial Q^*}{\partial x_i}=-\frac{(1+\beta)}{2}\left(-p'Q^*+\hat{t}\right)\frac{\partial Q^*}{\partial\hat{t}}=-\frac{(1+\beta)}{2}\left(\frac{\partial W_M^u}{\partial\hat{t}}-Q^*\right). \tag{12}$$

Differentiating Eq. 12 with respect to $\hat{t}$ yields

$$\frac{\partial^2 W_M^u}{\partial x_i\partial\hat{t}}=-\frac{(1+\beta)}{2}\left(\frac{\partial^2 W_M^u}{\partial\hat{t}^2}-\frac{\partial Q^*}{\partial\hat{t}}\right).$$

Thus, we have

$$\frac{\partial\hat{t}^*}{\partial x_i}=-\frac{\partial^2 W_M^u/\partial x_i\partial\hat{t}}{\partial^2 W_M^u/\partial\hat{t}^2}=\frac{(1+\beta)}{2}\left(1-\frac{\partial Q^*/\partial\hat{t}}{\partial^2 W_M^u/\partial\hat{t}^2}\right)=\frac{(1+\beta)}{2}\left[1-\frac{p'}{\Delta_1\left(g_{ii}+g_{ij}\right)}\right], \tag{13}$$

where $\partial^2 W_M^u/\partial\hat{t}^2$ can be shown to equal $2(g_{ii}{+}g_{ij})$. Equations 11 and 13 show that $\partial t_i^*/\partial x_i + \partial t_j^*/\partial x_i = 2\left(\partial\hat{t}^*/\partial x_i\right)$. Since $\partial t_i^*/\partial x_i - \partial t_j^*/\partial x_i \ge 0$ from Eq. 4, we have $\partial t_j^*/\partial x_i \le \partial\hat{t}^*/\partial x_i \le \partial t_i^*/\partial x_i$, where the equality holds when $\beta{=}1$. Thus, $\partial\pi_i^d/\partial x_i|_{x_1=x_2=x^u} \le 0$, implying that $x^d{\le}x^u$, where the equality holds when $\beta{=}1$. ■

Choi (1995) shows that technology with a lower marginal cost will be chosen under a uniform tariff regime. The model of Choi (1995) corresponds to the special case of $\beta{=}0$ in the present model, and we show that the argument of Choi (1995) still holds with some degree of R&D spillovers, as long as the effect of the R&D spillovers is not completely perfect. This can be shown intuitively as follows. When $\beta{\neq}1$, $\partial t_i*/\partial x_i < \partial*/\partial x_i < \partial t_i*/\partial x_i$, so under a discriminatory tariff regime a firm has a disincentive to invest in R&D because this has a greater adverse effect on its own tariff than on that of its rival. This own-tariff effect leads to the chosen R&D level being lower under a discriminatory tariff regime than under a uniform tariff regime. When $\beta{=}1$, $\partial t_j^*/\partial x_i = \partial\hat{t}^*/\partial x_i = \partial t_i^*/\partial x_i$, so the firms are indifferent to the tariff regime and the choice of R&D level under the two tariff regimes will be the same.

As long as the two exporting firms choose the same R&D level, the welfare of country M is independent of the tariff regime; that is, $W_M^d(x,x) = W_M^u(x,x)$. Moreover, it is easy to show that, under either tariff regime, a rise in R&D simultaneously chosen by both firms, with country M choosing the optimal tariff, will benefit country M. The intuition is that a simultaneous rise in R&D will lower the price of the product, thus benefiting country M. Lemma 1 shows that $x^d \leq x^u$, so we have $W_M^d(x^d,x^d) = W_M^u(x^d,x^d) \leq W_M^u(x^u,x^u)$. With the condition $\partial\hat{t}^*/\partial x_i > 0$, we also have $t_1^*(x^d,x^d) = t_2^*(x^d,x^d) = \hat{t}^*(x^d,x^d) \leq \hat{t}^*(x^u,x^u)$. If $\partial\hat{t}^*/\partial x_i = 0$, meaning that the level of R&D has no effect on the uniform tariff, then $t_1^*(x^d,x^d) = t_2^*(x^d,x^d) = \hat{t}^*(x^d,x^d) = \hat{t}^*(x^u,x^u)$. Thus, we have the following proposition:

Proposition 2 *Suppose that the two firms are identical.*

(1) *If* $\beta \neq 1$, *the importing country will optimally choose a uniform tariff regime. If* $\beta = 1$, *the importing country is indifferent to the tariff regime.*
(2) *If* $\beta \neq 1$ *and* $\partial\hat{t}^*/\partial x_i > 0$, *the uniform tariff rate is higher than the discriminatory tariff rate. If* $\beta = 1$ *or* $\partial\hat{t}^*/\partial x_i = 0$, *the uniform tariff rate equals the discriminatory tariff rate.*

Under the conditions that $\beta \neq 1$ and $\partial\hat{t}^*/\partial x_i > 0$, we confirm the result of Horiba and Tsutsui (2000) that the uniform tariff rate is higher than the discriminatory tariff rate. This is because the R&D level is higher under a uniform tariff regime, leading to the tariff being higher than that imposed under a discriminatory tariff regime.

We now turn to the effects of the tariff regimes on the profits of the exporting firms. Suppose that the firms can cooperate when choosing the R&D investment that will maximize their joint profits, $(\pi_1 + \pi_2)$. The first-order condition for firm i when choosing x_i to maximize their joint profits is given by $\partial(\pi_1 + \pi_2)/\partial x_i = 0, \;\; i = 1,2$. We denote the common, cooperative R&D level for each firm by $\tilde{x}$.[10] We have the following lemma:

Lemma 2 *Suppose that the two firms are identical and* $\partial\hat{t}^*/\partial x_i \geq 0$. *The ranking of* x^d, x^u, *and* $\tilde{x}$ *depends on the degree of R&D spillovers as follows:*

(1) $\tilde{x} < x^d < x^u$ if $0 \leq \beta < \beta_1$,
(2) $\tilde{x} = x^d < x^u$ if $\beta = \beta_1$,
(3) $x^d < \tilde{x} < x^u$ if $\beta_1 < \beta < \beta_2$,
(4) $x^d < x^u = \tilde{x}$ if $\beta = \beta_2$,
(5) $x^d < x^u < \tilde{x}$ if $\beta_2 < \beta < 1$,
(6) $x^d = x^u < \tilde{x}$ if $\beta = 1$.

[10] $\tilde{x}$ is independent of the tariff regime because in either regime the same R&D level will be chosen for both firms and country M will implement with a common tariff rate.

Proof Consider a discriminatory tariff regime. With the assumption $c_1 = c_2$, $q_1^* = q_2^* = q^* = Q^*/2$. Differentiating π_j^d with respect to x_i yields

$$\begin{aligned}\frac{\partial \pi_j^d}{\partial x_i} &= q^*\left[\beta - \frac{\partial t_j^*}{\partial x_i} + p'\left(\frac{\partial q_i^*}{\partial t_i}\frac{\partial t_i^*}{\partial x_i} + \frac{\partial q_i^*}{\partial t_j}\frac{\partial t_j^*}{\partial x_i} + \frac{\partial q_i^*}{\partial x_i}\right)\right] \\ &= q^*\left[\frac{1+\beta}{2} - \frac{p''q^*(1-\beta)+p'(3-\beta)}{2\left(p''Q^*+3p'\right)} - \left(\frac{p''Q^*+2p'}{p''Q^*+3p'}\right)\left(\frac{\partial t_i^*}{\partial x_i}\right)\right].\end{aligned}$$

When $\beta=1$, $\partial\pi_j^d/\partial x_i > 0$, so $\partial\left(\pi_1^d + \pi_2^d\right)/\partial x_i|_{x_1=x_2=x^d} > 0$, implying that $x^d < \widetilde{x}$. Given that $\partial\hat{t}^*/\partial x_i \geq 0$, we have $\partial t_i^*/\partial x_i \geq (1-\beta)/4$ because $\partial\left(t_i^* + t_j^*\right)/\partial x_i = 2\left(\partial\hat{t}^*/\partial x_i\right)$ and $\partial\left(t_i^* - t_j^*\right)/\partial x_i = (1-\beta)/2$. When $\beta=0$, $\partial t_i^*/\partial x_i \geq 1/4$, and we have

$$\begin{aligned}\frac{\partial \pi_j^d}{\partial x_i} &= q^*\left[\frac{p''q^*}{2\left(p''Q^*+3p'\right)} - \left(\frac{p''Q^*+2p'}{p''Q^*+3p'}\right)\left(\frac{\partial t_i^*}{\partial x_i}\right)\right] \\ &\leq q^*\left[\frac{p''q^*}{2\left(p''Q^*+3p'\right)} - \frac{p''q^*+p'}{2\left(p''Q^*+3p'\right)}\right] < 0.\end{aligned}$$

Thus, $\partial\left(\pi_1^d + \pi_2^d\right)/\partial x_i|_{x_1=x_2=x^d} < 0$, implying that $\widetilde{x} < x^d$. Since $\partial\pi_j^d/\partial x_i > 0$ at $\beta=1$ and $\partial\pi_j^d/\partial x_i < 0$ at $\beta=0$, there exists a value of $\beta_1 \in (0,1)$ such that $\partial\pi_j^d/\partial x_i = 0$ and $\widetilde{x} = x^d$. β_1 satisfies the following condition:

$$1 + \beta_1 - \frac{p''q^*(1-\beta_1) + p'(3-\beta_1)}{(p''Q^* + 3p')} - 2\left(\frac{p''Q^* + 2p'}{p''Q^* + 3p'}\right)\left(\frac{\partial t_i^*}{\partial x_i}\right) = 0. \tag{14}$$

Now, differentiating π_j^u with respect to x_i yields

$$\begin{aligned}\frac{\partial \pi_j^u}{\partial x_i} &= q^*\left[\beta - \frac{\partial\hat{t}^*}{\partial x_i} + p'\left(\frac{\partial q_i^*}{\partial\hat{t}}\frac{\partial\hat{t}^*}{\partial x_i} + \frac{\partial q_i^*}{\partial x_i}\right)\right] \\ &= q^*\left[\beta - \frac{\partial\hat{t}^*}{\partial x_i} + \left(\frac{p'}{p''Q^*+3p'}\right)\frac{\partial\hat{t}^*}{\partial x_i} + \frac{p''q^*(\beta-1)+p'(\beta-2)}{p''Q^*+3p'}\right] \\ &= q^*\left[\beta - \frac{p''q^*(1-\beta)+p'(2-\beta)}{p''Q^*+3p'} - \left(\frac{p''Q^*+2p'}{p''Q^*+3p'}\right)\frac{\partial\hat{t}^*}{\partial x_i}\right].\end{aligned}$$

When $\beta=1$, $\partial\pi_j^u/.\partial x_i > 0$, so $\partial\left(\pi_1^u + \pi_2^u\right)/\partial x_i|_{x_1=x_2=x^u} < 0$, implying that $x^u < \widetilde{x}$. When $\beta=0$, given that $\partial\hat{t}^*/\partial x_i \geq 0$, $\partial\pi_j^u/\partial x_i < 0$, so $\partial\left(\pi_1^u + \pi_2^u\right)/\partial x_i|_{x_1=x_2=x^u} < 0$, implying that $\widetilde{x} < x^u$. There exists a value of $\beta_2 \in (0,1)$ such that $\partial\pi_j^u/\partial x_i = 0$ and $\widetilde{x} = x^u$. β_2 satisfies the following condition:

$$\beta_2 - \frac{p''q^*(1-\beta_2) + p'(2-\beta_2)}{p''Q^* + 3p'} - \left(\frac{p''Q^* + 2p'}{p''Q^* + 3p'}\right)\frac{\partial\hat{t}^*}{\partial x_i} = 0. \tag{15}$$

We next want to show that $\beta_1 < \beta_2$. Subtracting Eq. 14 from Eq. 15 yields

$$(\beta_2 - \beta_1)\left(\frac{3p''q^* + 4p'}{p''Q^* + 3p'}\right) + \left(2\frac{\partial t_i^*}{\partial x_i} - \frac{\partial\hat{t}^*}{\partial x_i} - 1\right)\left(\frac{p''Q^* + 2p'}{p''Q^* + 3p'}\right) = 0,$$

where $2\left(\partial t_i^*/\partial x_i\right) - \left(\partial\hat{t}^*/\partial x_i\right) - 1 < 0$. Therefore, $\beta_1 < \beta_2$. ∎

Lemma 2 can be linked to the existing results: if spillovers are sufficiently low, the noncooperative R&D level (either x^d or x^u) exceeds the cooperative R&D level ($\widetilde{x}$); whereas if spillovers are sufficiently high, x^d and x^u are smaller than $\widetilde{x}$.

The profit ranking of the two tariff regimes for the firms depends on the ranking of the R&D levels, which in turn depends on the degree of R&D spillovers. If $0 \leq \beta \leq \beta_1$, firms acting noncooperatively will overinvest in R&D more under a uniform tariff regime than under a discriminatory tariff regime, and hence they will be better off under the latter. On the other hand, if $\beta_2 \leq \beta < 1$, firms acting noncooperatively will underinvest in R&D more under a discriminatory tariff regime than under a uniform tariff regime, and hence they will be better off under the latter. If $\beta = 1$, they are indifferent to the tariff regime. If $\beta_1 < \beta < \beta_2$, then $x^d < \tilde{x} < x^u$, implying that the firms overinvest (underinvest) under a uniform (discriminatory) tariff regime. We define β_{cv} as the critical value that makes $\pi^d(x^d) = \pi^u(x^u)$, and make the following proposition:

Proposition 3 *Suppose that the two firms are identical and $\partial \hat{t}^* / \partial x_i \geq 0$. Both firms prefer a discriminatory tariff regime if $0 \leq \beta < \beta_{cv}$, while they prefer a uniform tariff regime if $\beta_{cv} < \beta < 1$. They are indifferent to the tariff regime if $\beta = \beta_{cv}$ or $\beta = 1$.*

To illustrate the general result of Proposition 3, let us consider the linear demand case where $p = a - bQ$. It can be shown that $\beta_1 = 1/3$, $\beta_2 = 3/5$, and β_{cv} satisfies the following condition: $7\beta_{cv}^3 - 11\beta_{cv}^2 + (64b\gamma - 11)\beta_{cv} + (7 - 32b\gamma) = 0$.[11] Figure 1 shows how $\tilde{\pi}$, π^d, and π^u vary with β, where $\tilde{\pi}$ is the cooperative profit when each firm chooses $\tilde{x}$. It can be seen that the firms are better off under a uniform (discriminatory) tariff regime when $\beta > (<) \beta_{cv}$. They are indifferent to the tariff regime when $\beta = \beta_{cv}$ or $\beta = 1$. When $\beta = 1/3(3/5)$, the noncooperative profit under a discriminatory (uniform) tariff regime reaches the cooperative profit.

Corresponding to the special case of $\beta = 0$ in our model, Choi (1995) shows that the exporting firms are better off under a discriminatory tariff regime. When $\beta \neq 0$, Proposition 3 shows that the exporting firms would prefer a uniform tariff regime if the spillover effect is sufficiently large. Therefore, both the importing country and the exporting firms would prefer the same tariff regime if the degree of R&D spillovers is above a threshold level, β_{cv}.

4 Does free trade improve welfare and profits?

Gatsios (1990) and Hwang and Mai (1991) show that the importing country prefers discriminatory tariffs when the cost structures of the foreign exporters are given exogenously. However, ex ante cost-reducing R&D choice, we show that the importing country prefers a uniform tariff regime because the exporters invest more in R&D under a uniform tariff regime than under a discriminatory tariff regime. The results in Gatsios (1990) and Hwang and Mai (1991) also imply that, ex post cost-reducing R&D choice, the importing country prefers tariffs (either uniform or discriminatory) to free trade. One may ask whether, ex ante cost-reducing R&D choice, the importing country would prefer free trade to tariffs because the exporters would choose a higher R&D level under free trade than under either tariff regime. To

[11] β_{cv} decreases as $b\gamma$ increases, and as $b\gamma \to \infty$, $\beta_{cv} \to 0.5$.

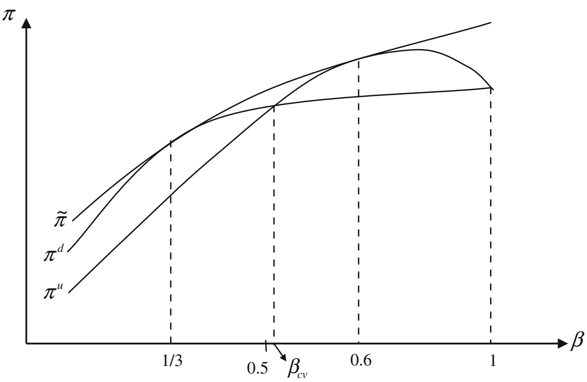

Fig. 1 Comparison of $\tilde{\pi}$, π^d, and π^u

answer this question, we consider the free trade case in which the game has three stages. In the first stage, country M announces the adoption of a free trade policy. In the second stage, the firms choose R&D levels, and in the third stage, the firms determine the quantities they export to country M. Suppose again that the two firms are identical. To make the solutions of the games under free trade and under uniform/discriminatory tariffs both tractable and comparable, we assume a linear demand. We denote the equilibrium R&D level and the welfare of country M under free trade as x^{ft} and W_M^{ft}, respectively. It can be easily shown that $x^d \leq x^u < x^{ft}$, where the equality holds when $\beta=1$. Thus, the equilibrium R&D level under free trade is always larger than that under either tariff regime.

Country M faces a trade-off when choosing between free trade and tariffs: a gain in consumer surplus due to a larger R&D investment by the firms under free trade versus a loss in tariff revenue under free trade. We define β^* as the critical value that makes $W_M^{ft} = W_M^u$, and make the following proposition:

Proposition 4 *Suppose that the two firms are identical and the demand is linear. The importing country prefers free trade over either tariff regime if one of the following conditions holds:* (1) $b\gamma<2.6196$, (2) $2.6196 \leq b\gamma \leq 3.6499$ *and* $\beta>\beta^*$; *otherwise it prefers a uniform tariff regime.*

Proof See the Appendix. ■

Proposition 4 shows that the optimal tariff policy (free trade vs. uniform tariff) of the importing country depends on the values of b, γ, and β. The importing country would be better off under free trade when $b\gamma$ is small (i.e., either the demand is relatively more elastic with a lower b, or the R&D investment is relatively more efficient with a lower γ, or both), or when $b\gamma$ is moderate and the R&D spillover effect is sufficiently large. In such cases the cost-reducing R&D has a greater positive impact on total output and consumer surplus, so if country M adopts free trade, the gain in consumer surplus outweighs the loss in tariff revenue. Note that the credibility of the free trade policy adopted by country M and its commitment to it are crucial to this result. The results on Gatsios (1990) and Hwang and Mai (1991) imply that, ex post cost-reducing R&D choice, country M has an incentive to impose tariffs. Thus, if the exporters do not consider the free trade policy credible, they would make their R&D decisions based on the belief that country M will impose tariffs later even though it already announced a free trade policy.

Considering the impacts of different tariff policies on the profits of the exporting firms, we have the following proposition:

Proposition 5 *Suppose that the two firms are identical and the demand is linear. A discriminatory tariff regime is preferred by the exporting firms if* $b\gamma < 1.153$ *and* $\beta < \beta_{fd}$*; otherwise they prefer free trade.*

Proof See the Appendix. ■

Proposition 5 is an interesting result, showing that the exporting firms would prefer discriminatory tariffs to free trade when both $b\gamma$ and β are sufficiently small. When $b\gamma$ is small, the cost-reducing R&D has a greater positive impact on total output. Lemma 2 shows that the two firms overinvest in R&D when β is small, and hence that their profits would increase if they reduce the R&D level. Under free trade the firms choose an even larger R&D investment (i.e., $\widetilde{x} < x^d < x^u < x^{ft}$), making the overinvestment problem even worse. Thus, when both $b\gamma$ and β are sufficiently small, the loss in profit due to overinvestment in R&D outweighs the savings in tariff payments under free trade. The firms thus would be better off under a discriminatory tariff regime.

Combining Propositions 4 and 5 reveals that the importing country and the exporting firms all prefer free trade if one of the following conditions holds: (1) $b\gamma <$ 1.153 and $\beta > \beta_{fd}$, (2) $1.153 \le b\gamma < 2.6196$, (3) $2.6196 \le b\gamma \le 3.6499$ and $\beta > \beta^*$.[12] Since the importing country may have an incentive to deviate from free trade and impose tariffs after the R&D choice has been made, an enforcement mechanism for ensuring the continuation of free trade once the importing country has committed to it is crucial for improving both the welfare of the importing country and the profits of the two exporting firms. This result provides strong support for the WTO to promote trade liberalization, because the commitment of the importing country to a free trade policy becomes credible if it has to follow the WTO trade liberalization rule.

5 Concluding remarks

This paper has investigated the effects of R&D spillovers on the R&D choices of foreign exporters in the presence of tariffs imposed by the importing country. While the two exporters make cost-reducing R&D investments to compete in quantities, the importing country uses tariffs to extract rents from the exporters. Our comparison of uniform and discriminatory tariff regimes based on the welfare of the importing

[12] Horiba and Tsutsui (2000) show that when the decision on the long-run capacity becomes increasingly relevant to that on the short-run quantity, both the importing country and the exporting firms prefer free trade. However, in their work the exporting firms always prefer free trade, whereas Proposition 5 shows that the exporting firms may prefer discriminatory tariffs over free trade in certain circumstances.

country and the profits of the exporting firms reveals that, at least in the case when the firms are identical with the same initial marginal cost, the importing country should optimally choose a uniform tariff regime. This result is contrary to the widespread belief that a discriminatory tariff regime should dominate over a uniform tariff regime because under the former the country can also choose the same tariffs. We suggest that this preconception does not hold in the present model because the exporting firms invest more in R&D under a uniform tariff regime, leading to a lower market price and thus also benefiting the importing country. When spillovers are sufficiently large, we show that the exporting firms also prefer a uniform tariff regime.

Comparison of free trade with the two tariff regimes reveals that the importing country can benefit from a precommitment to free trade in some cases. This is because the firms choose a higher R&D level under free trade, leading to a higher consumer surplus in the importing country. The gain in consumer surplus outweighs the loss in tariff revenue, so the importing country is better off under free trade. We have also described situations in which the importing country and the exporting firms are all better off under free trade, supporting the argument for WTO trade liberalization.

The analysis of this paper is based on the model of "competition in the third market," with no consumption in the two exporting countries and no production in the importing country. Saggi (2004) uses a more realistic and general model that allows for consumption in exporting countries and production in importing countries. Our model can be easily extended to the case where importing country M has a domestic firm, and it competes with foreign exporters in the market of country M. Since the main purpose of this paper is to analyze the welfare effects of the tariff regimes through the R&D investments by foreign exporters for various degrees of R&D spillovers, it can be shown that our qualitative results do not change if we assume that there is no R&D spillover between the domestic firm and the foreign exporters. A model for analyzing the R&D choices of the domestic firm and the foreign exporters in the presence of different degrees of R&D spillovers among the firms deserves future investigation.

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Appendix

Proof of Proposition 4

We define β^* as the critical value that makes $W_M^{ft} = W_M^u$, where it satisfies the following condition:

$$\begin{aligned} &47\beta^{*4} - 148\beta^{*3} + (288b\gamma - 150)\beta^{*2} + (332 - 576b\gamma)\beta^* \\ &\quad + (287 - 864b\gamma + 288b^2\gamma^2) \\ &\quad = 0. \end{aligned}$$

The simulation results show that when $b\gamma<2.6196$, $W_M^{ft} > W_M^u$ for $\beta\in[0,1]$; when $2.6196\leq b\gamma\leq 3.6499$, $W_M^{ft} > (<) W_M^u$ if $\beta>(<)\beta^*$; and when $b\gamma>3.6499$, $W_M^{ft} < W_M^u$ for $\beta\in[0,1]$.

Proof of Proposition 5

To determine whether a free trade policy is preferred by the exporting firms, we first compare π^{ft} with π^d. We define β_{fd} as the critical value that makes $\pi^{ft}=\pi^d$, where it satisfies the following condition:

$$\begin{aligned}50.5\beta_{fd}^4 - 175\beta_{fd}^3 + (84 + 379.75b\gamma)\beta_{fd}^2 + (175 - 902.5b\gamma)\beta_{fd} \\ -(134.5 - 697.75b\gamma + 504b^2\gamma^2) \\ = 0.\end{aligned}$$

The simulation results show that when $b\gamma\geq 1.153$, $\pi^{ft}>\pi^d$ for $\beta\in[0,1]$; and when $b\gamma< 1.153$, $\pi^{ft}>(<)\pi^d$ if $\beta>(<)\beta_{fd}$. We next compare π^{ft} with π^u. We define β_{fu} as the critical value that makes $\pi^{ft}=\pi^u$, where it satisfies the following condition:

$$\begin{aligned}6.5\beta_{fu}^4 - 107\beta_{fu}^3 + (168 - 70.25b\gamma)\beta_{fu}^2 + (107 - 416.5b\gamma)\beta_{fu} \\ -(174.5 - 661.75b\gamma + 504b^2\gamma^2) \\ = 0.\end{aligned}$$

The simulation results show that when $b\gamma\geq 0.9477$, $\pi^{ft}>\pi^u$ for $\beta\in[0,1]$; and when $b\gamma<0.9477$, $\pi^{ft}>(<)\pi^u$ if $\beta>(<)\beta_{fu}$. Moreover, it can been shown that $\beta_{fu}<\beta_{fd}<\beta_{cv}$ for any value of $b\gamma$. Thus, for $\beta<\beta_{fd}$, we know that $\pi^u<\pi^d$ from Proposition 3.

Thus, when $b\gamma\geq 1.153$, $\pi^{ft}>\pi^d$ and $\pi^{ft}>\pi^u$ for $\beta\in[0,1]$; when $0.9477\leq b\gamma<1.153$, $\pi^{ft}>\pi^d$ and $\pi^{ft}>\pi^u$ if $\beta>\beta_{fd}$, and $\pi^u<\pi^{ft}<\pi^d$ if $\beta<\beta_{fd}$; and when $b\gamma<0.9477$, $\pi^{ft}>\pi^d$ and $\pi^{ft}>\pi^u$ if $\beta>\beta_{fd}$, and $\pi^{ft}<\pi^d$ and $\pi^u<\pi^d$ if $\beta<\beta_{fd}$.

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