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Unilateral Emission Standards, Quality of Vertically Differentiated Products, and the Global Environment †

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Abstract

Employing an environmentally-differentiated products model with heterogeneous consumers in terms of environmental consciousness, this paper examines the effect of a unilateral change in a home emission standard on the qualities of products, aggregate emissions, and welfare of both home and foreign countries. When firms compete with each other in a Cournot fashion, as the home emission standard becomes stricter, aggregate emissions of both domestic and foreign countries decrease, if a firm which produces a "dirtier product"' supplies the same product to both domestic and foreign markets. On the other hand, if the firm supplies different products in environmental features to different markets, a stricter emission standard by the home government increases aggregate emissions of the foreign country. Even in the Bertrand duopoly case, the effects of a stricter emission standard on both countries could be different from each other.

JEL Classification: D43; F12; Q28.
Key words: emission standards; international duopoly; environmentally differentiated products.

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1. Introduction

People become more environmentally conscious as their country develops and per capita income increases. Accordingly, there exist growing concerns about emissions and health problems arising from the consumption of products. Governments usually respond to this situation by adopting various kinds of standards on emissions and other types of consumption-related environmental and health problems. For example, many countries have emission standards on motor vehicle exhaust: some are very strict, whereas others are relatively lax.[1] Moreover, many countries have strict standards on food safety, such as on food additives and the residuals of agrochemicals, although international standards exist.[2]

Faced with these standards, firms improve the quality of their products, particularly in their environmental and health aspects. In the case of motor vehicles, some automakers have improved fuel efficiency drastically, whereas others have developed hybrid or electric vehicles. Because the strictness of standards varies from one country to another, firms that supply their products to more than one country must comply with various types of regulations. In some cases, they make products that differ in terms of environmental quality according to the number of markets they enter. In other cases, they supply the same type of product to more than one market, because it is costly to supply more than one type of product.[3]

Observing the behavior of these firms regarding the number of types of products they supply, it is natural to consider that a change in an emission standard in one country

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[1] For example, see the following website for the EU standards: http://europa.eu/legislation_summaries/environment/air_pollution/index_en.htm. For the United States, see http://www.epa.gov/otaq/standards/ (Environmental Protection Agency). The Republic of Korea has determined that it will adopt standards similar to those of the EU.

[2] For example, see http://www.mhlw.go.jp/english/topics/foodsafety/index.html (Ministry of Health, Labor, and Welfare) for the case of Japan. The international standard is called the CODEX standard. See http://www.codexalimentarius.net/ for details.

[3] For example, it may be difficult for one automaker to supply both hybrid and electric vehicles at the same time, because it has to invest in R&D, plants, supply chains, and recycling systems.

influences other countries' markets, and that the effect on the domestic market may differ from that on the foreign market.

Focusing on the emissions from consumption, this paper investigates the effect of a unilateral change in an emission standard in one country on the product quality, aggregate emissions, and welfare of both the domestic and the foreign countries.

During the past few decades, a considerable number of studies have examined the effect of environmental policies in an open economy, when pollution is emitted in the production process (see Conrad (1993), Kennedy (1994), Ulph (1996, 1999), Rauscher (1997), and Neary (2006), among others). However, relatively few studies have examined environmental policies and international trade when pollution is emitted in the consumption process, in particular, when consumers are heterogeneous. Motta and Thisse (1999) examine the effect of a minimum environmental-quality standard on firms' behavior and international trade strategies. However, in comparing welfare in different situations, they do not take into consideration environmental damage. Moraga-González and Padrón-Fumero (2002) investigate the effects of various environmental policies in a model with vertically differentiated products. However, they consider only Bertrand competition. Moreover, neither study considers the number of types of products chosen by firms.

Based on Moraga-González and Padrón-Fumero (2002), we employ a differentiated products model with heterogeneous consumers in terms of environmental consciousness. Some consumers prefer an environmentally friendly product to an environmentally unfriendly product even if the former is more expensive than the latter; others, however, prefer the latter to the former. Therefore, when two firms enter the market with these consumers, their products are differentiated by environmental features. Toshimitsu (2008a) employs this type of model, and analyzes the effect of the setting of emission standards by one country on its own welfare when two foreign firms enter the domestic market.[4] By contrast, we analyze the effect not only on the domestic market but also on the foreign market, and examine whether or not the effects are the same in both countries. Usually, it is considered that a unilateral emission standard improves the quality of imported products. Even if this effect is beneficial for the domestic environment, this does not necessarily lead to a decrease in aggregate emissions from consumption in the foreign market. Thus, it is important to clarify what effect a change in a unilateral emission standard has on the environment.

In terms of the purpose of this paper, our model has two important features. First, to extract the essence of our focus, we consider the duopoly case in which one firm supplies a “dirtier product” and the other supplies a “cleaner product” to both the home and foreign markets. Because the emission standard we focus on is the upper limit of emission levels per unit of consumption, any change in the level of an emission standard directly influences the dirtier product. Moreover, to examine whether or not the results depend on the mode of competition, we consider two types of basic duopoly models: Cournot duopoly and Bertrand duopoly.

Second, the firm that produces dirtier products may produce more than one type of dirtier product in terms of environmental characteristics. This means that, when the firm supplies its products to two countries (home and foreign), (a) the firm produces two types of dirtier products, (b) each type of product is supplied to either the home or the foreign market, and (c) only one type is supplied to each market.

When the focus is on emissions in the production process, firms’ location choices are crucial in understanding the effect of environmental policies. For example, Markusen et al.

[4] Toshimitsu (2008b) also applies this model to investigate the effect of a tariff on the domestic environment and welfare.

(1993) examines the effect of environmental policies on the aggregate emissions when plant locations are endogenously determined.[5] By contrast, because we focus on emissions in the consumption stage, the number and quality of products supplied are crucial.

The main results are as follows. Suppose that firms compete with each other in a Cournot fashion in both home and foreign markets. Then, as an emission standard set by the home country becomes stricter, aggregate emissions of both home and foreign countries decrease if the firm that produces a 'dirtier product' supplies the same product to both markets. However, if the firm supplies different types of dirtier products to each market, as the home emission standard becomes stricter, the aggregate emissions of the foreign country increase. Even in the Bertrand duopoly case, a stricter home emission standard could have different effects on the two countries. Moreover, we refer to endogenous determination of the number of types of products produced by the firm that produces dirtier products.

The structure of the paper is as follows. Section 2 sets up the model. Section 3 describes the equilibria in the Cournot and Bertrand duopoly cases. Section 4 examines the effect of a stricter emission standard on product quality, aggregate emissions, and the welfare of both countries. Section 5 investigates endogenous determination of the number of types of dirtier products. Sections 6 and 7 provide further discussion and concluding remarks, respectively.

2. The Model

2.1 Markets

We consider a vertically differentiated product model, in which 'vertically differentiated' implies 'environmentally differentiated'. There are two countries: the home country, which is denoted by h, and the foreign country, which is denoted by f. In each country, there exists

[5] Many other analyses have been made on this issue. See Markusen (1997) and Ulph and Valentini (1997), among others.

a continuum of heterogeneous consumers who differ in their marginal valuations, θ, of the green features of a product. To simplify, we assume that the distribution of consumers is identical in both countries, and that the consumer-matching value is uniformly distributed in the market in each country, $\theta \in [0,1]$. A consumer for whom θ is close to unity (resp. zero) is conscious (resp. not conscious) of the environment. Let e denote the observable level of polluting emissions associated with the unit consumption of a product. Each consumer purchases either one or no units of the product. The net surplus of consumer θ in country i who acquires the variant e at price p_i is $u = \max\{v - e\theta - p_i, 0\}$, $e \in (0, \infty)$, where v is the utility obtained from consuming a single unit of the product irrespective of the variant's unit emission level. A consumer who does not buy any product is assumed to have a net surplus of zero.

There are two firms outside these two consuming countries, which supply environmentally differentiated products to both countries h and f (see Figure 1).[6] Without loss of generality, we assume that firm D (resp. C) supplies a product with a unit emission level $e_{D,i}$ (resp. $e_{C,i}$) at price $p_{D,i}$ (resp. $p_{C,i}$) to the market of country i ($i = h, f$), and that $e_{D,i} > e_{C,i}$. Thus, two types of products are supplied to each country. In the following, we call the product produced by firm D the dirtier product, and the product produced by firm C the cleaner product.

We derive the demand functions for those differentiated products in country i. The index of the marginal consumer who is indifferent between the net surplus given by purchasing the dirtier and the cleaner products is characterized by $\tilde{\theta}_i = (p_{C,i} - p_{D,i})/(e_{D,i} - e_{C,i})$. However, the index of the marginal consumer who is

[6] The reason assume the two firms are located outside these two consuming countries is that we focus on pollution emissions from consumption and, accordingly, the conflict between the consumer's surplus and environmental damage. We investigate producer's surplus in Section 6.

indifferent between the net surplus given by purchasing the cleaner product and nothing is $\hat{\theta}_i = \left(v - p_{C,i}\right)/e_{C,i}$. Thus, consumer θ falling into $0 \le \theta \le \tilde{\theta}$ (resp. $\tilde{\theta} < \theta \le \hat{\theta}$) purchases a dirtier (resp. cleaner) product, and consumer θ falling into $\hat{\theta} < \theta \le 1$ purchases nothing.[7] Throughout the paper, it is assumed that neither country's market is completely covered by all consumers.

Let $q_{D,i}$ (resp. $q_{C,i}$) represent the quantity demanded of the dirtier (resp. the cleaner) product in country i. Because a uniform distribution is assumed, the demand functions are given by:

$$q_{D,i} = \tilde{\theta}_i = \frac{p_{C,i} - p_{D,i}}{e_{D,i} - e_{C,i}}, \tag{1.1}$$

$$q_{C,i} = \hat{\theta}_i - \tilde{\theta}_i = \frac{e_{D,i}\left(v - p_{C,i}\right) - e_{C,i}\left(v - p_{D,i}\right)}{e_{C,i}\left(e_{D,i} - e_{C,i}\right)}. \tag{1.2}$$

Given (1.1) and (1.2), the corresponding inverse demand functions are given by:

$$p_{D,i} = v - e_{D,i} q_{D,i} - e_{C,i} q_{C,i}, \tag{2.1}$$

$$p_{C,i} = v - e_{C,i}\left(q_{D,i} + q_{C,i}\right). \tag{2.2}$$

2.2 Firms

Before price or quantity competition in the markets, the firms need to invest in product lines, a supply network, and recycling systems with the associated environmental quality of the products. Following Moraga-González and Padrón-Fumero (2002, Assumption 2), we assume that the cost function of a unit emission level for each firm can be expressed by a homogeneous function of degree $\varepsilon \ge 1$:

$$F_D\left(e_D\right) = \alpha\, e_D^{-\varepsilon}, \tag{3.1}$$

[7] It can also be considered that consumer θ falling into $\hat{\theta} < \theta \le 1$ purchases the outside good.

$$F_C(e_C) = e_C^{-\varepsilon}. \quad (3.2)$$

Note that $F_j' < 0$, $F_j'' > 0$, $j = C, D$. To avoid multiple equilibria in the decision game of the unit emission levels, we assume that cost functions are sufficiently asymmetric among the firms: $\alpha > 1$. This implies that firm C (resp. D) has an efficient (resp. inefficient) environmental technology. For simplicity, we assume that marginal costs of production are independent of the unit emission levels and are equal to zero.

Firm D can choose different unit emission levels for different markets, i.e., $e_{D,h} \neq e_{D,f}$. In such a case, however, it has to pay an additional fixed cost for the production of another dirtier product, such as another product line, and an additional recycling network.[8] In the main analysis in Section 4, the number of types of products produced by firm D is exogenous, whereas in Section 5 we investigate the case in which the number of types of products produced by firm D is endogenously determined. In the following, the statements "firm D produces two types of products" and "firm D supplies different types of products to each market" mean that (a) firm D produces two types of dirtier products, (b) each type is supplied to either the home or the foreign market, and (c) only one type is supplied to each country/market.

Because we focus on an emission standard policy for a dirtier product, hereafter, we mainly assume that firm C supplies the same type of product to both markets.[9] This implies that firm C does not pay an additional fixed cost. Thus, the profit functions of the two firms are given by:

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[8] This fixed cost is not the cost for R&D. Thus, even if the unit emission level of the dirtier product for the foreign market is higher than that for the home market, firm D has to pay the additional cost. In particular, there are 'ex post' costs such as the cost of recycling materials included in the product for the foreign market.

[9] In reality, as noted in footnote 3, it is sometimes very costly to supply more than one type of cleaner product. We briefly discuss the case in which firm C supplies more than one type of product in Section 6.

$$\pi_D = p_{D,h}q_{D,h} + p_{D,f}q_{D,f} - F_{D,h} - \sigma F_{D,f}, \tag{4.1}$$

$$\pi_C = p_{C,h}q_{C,h} + p_{C,f}q_{C,f} - F_C, \tag{4.2}$$

where σ is a dummy variable; $\sigma = 0$ if $e_{D,h} = e_{D,f}$, or $\sigma = 1$ if $e_{D,h} \neq e_{D,f}$.

2.3 Governments and Social Welfare

We assume that the home government unilaterally sets an emission standard, which is the highest emission per unit of consumption when a product is sold and consumed in the home market. Because $e_{D,h} > e_C$, the emission standard implies the highest emission per unit of consumption of the dirtier product, $\bar{e}_{D,h}$. This variable is a parameter in our model. We assume that there is no emission standard for the foreign market, or the foreign emission standard is not binding even if it exists ($e_{D,f} < \bar{e}_{D,f}$). On the contrary, $\bar{e}_{D,h}$ is always binding and, accordingly, $\bar{e}_{D,h} \leq e_{D,f}$.

The aggregate emissions, which increase environmental damage, are expressed by:

$$E_i = e_{D,i}q_{D,i} + e_{C,i}q_{C,i} \quad (i = h, f). \tag{5}$$

Then, the aggregate emissions level in the global economy is given by $E^G = E_h + E_f$. Furthermore, as mentioned above, there are three types of consumers: those purchasing the dirtier product, those purchasing the cleaner product, and those never purchasing any products in the market. Thus, the aggregate consumer surplus can be represented as:

$$CS_i = \int_0^{\tilde{\theta}_i} (v - e_{D,i}\theta)d\theta - p_{D,i}q_{D,i} + \int_{\tilde{\theta}_h}^{\hat{\theta}_h} (v - e_C\theta)d\theta - p_{C,i}q_{C,i}. \tag{6}$$

The social net surplus of each country is given by:[10]

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[10] We consider the profits of firms in Section 6. As noted in footnote 6, our main focus is on the conflict between the consumer's surplus and environmental damage when considering social surplus.

$$W_i = CS_i - \gamma_i E_i \quad i = h, f \ , \tag{7}$$

where $\gamma_i \geq 0 \left(i = h, f \right)$ is the marginal social valuation of environmental damage of country i.[11]

In what follows, we consider a three-stage game. In the first stage, the home government changes an emission standard applied to the dirtier product; this change is exogenous in this paper. In the second stage, the firms determine the unit emission levels, given the home emission standard. In the third stage, they compete in the markets in price or in quantity. We derive a subgame perfect Nash equilibrium for each mode of competition by backward induction.

3. Equilibria

3.1 Cournot Duopoly Case

As the derivation of the Cournot–Nash equilibrium in the final stage is straightforward, the derivation procedure is omitted. The equilibrium quantities in the third stage are given by:

$$q_{D,i}^C = \frac{1}{4e_{D,i} - e_C} v, \tag{8.1}$$

$$q_{C,i}^C = \frac{2e_{D,i} - e_C}{e_{C,i}\left(4e_{D,i} - e_C\right)} v \, , \tag{8.2}$$

where $i = h, f$. Superscript C denotes Cournot competition. Hence, the revenue functions in the second stage are expressed by:

$$R_D^C = \frac{\bar{e}_{D,h}}{\left(4\bar{e}_{D,h} - e_C\right)^2} v^2 + \frac{e_{D,f}}{\left(4e_{D,f} - e_C\right)^2} v^2 \, , \tag{9.1}$$

[11] Equation (7) implies that each government takes into consideration its own environment only. However, this can be easily extended to the case in which emissions cross a national border.

$$R_C^C = \frac{\left(2\bar{e}_{D,h} - e_C\right)^2}{e_C\left(4\bar{e}_{D,h} - e_C\right)^2} v^2 + \frac{\left(2e_{D,f} - e_C\right)^2}{e_C\left(4e_{D,f} - e_C\right)^2} v^2 . \tag{9.2}$$

Because $\bar{e}_{D,h}$ is binding, firm D supplies the same type of product to both markets, $\bar{e}_{D,h} = e_{D,f}$. This implies that firm D does not solve the profit maximization problem in the second stage. However, when firm D chooses a unit emission level for the foreign market different from that for the home market, the first-order condition for profit maximization for firm D in the second stage is obtained as follows:

$$-\frac{4e_{D,f} + e_C}{\left(4e_{D,f} - e_C\right)^3} v^2 - F'_{D,f} = 0 . \tag{10.1}$$

However, firm C can choose the unit emission level of its own product by itself. From (4.2) and (9.2), the first-order condition is:

$$-\sum_i \frac{\left(2e_{D,i} - e_C\right)\left(8e_{D,i}^2 - 2e_{D,i}e_C + e_C^2\right)}{e_C^2\left(4e_{D,i} - e_C\right)^3} v^2 - F'_C = 0, \quad i = h, f, \quad e_{D,h} = \bar{e}_{D,h} . \tag{10.2}$$

It is assumed that the second-order conditions are satisfied. See Appendix 1 for details. Based on (10.1) and (10.2), let us define the reaction functions of the unit emission levels in the Cournot duopoly case as follows:

$$e_{D,f} = \phi_D^C\left(e_C\right), \ \phi_D'^C < 0 , \tag{11.1}$$

$$e_C = \phi_C^C\left(\bar{e}_{D,h}, e_{D,f}\right), \quad \partial\phi_C^C / \partial\bar{e}_{D,h} > 0, \ \partial\phi_C^C / \partial e_{D,f} > 0 . \tag{11.2}$$

Figure 2 shows these reaction functions when firm D chooses a unit emission level for the foreign market different from that for the home market. If firm D supplies the same type of dirtier product to both countries, the situation in the foreign market (the figure on the right) is the same as that in the home market (the figure on the left).

In view of (11.1), and (11.2), the unit emission levels of the products are strategic substitutes (resp. complements) with respect to firm D (resp. firm C) in the Cournot duopoly case (see Appendix 1). The intuition is as follows. An increase in the unit emission level of the cleaner (resp. the dirtier) product decreases (resp. increases) the difference in products' environmental quality. As the difference decreases (resp. increases), competition among the firms is intensified (resp. mitigated). Thus, the marginal revenue of increasing the unit emission level for firm D (resp. firm C) decreases (resp. increases).

Based on (11.1) and (11.2), when firm D chooses the unit emission level for the product supplied to the foreign market, there is a unique and stable Nash equilibrium, i.e., $\{e_{D,f}^{C}, e_{C}^{C}\}$, given $\bar{e}_{D,h}$. See Appendix 2.

3.2 Bertrand Duopoly Case

Similar to the Cournot duopoly case, the equilibrium quantities for the Bertrand duopoly case in the third stage are given by:

$$q_{D,i}^{B} = \frac{1}{4e_{D,i} - e_C} v, \tag{12.1}$$

$$q_{C.i}^{B} = \frac{2e_{D,i}}{e_C\left(4e_{D,i} - e_C\right)} v, \tag{12.2}$$

where $i = h, f$. Superscript B denotes Bertrand competition. Hence, the revenue functions in the second stage are expressed by:

$$R_D^B = \frac{\bar{e}_{D,h} - e_C}{\left(4\bar{e}_{D,h} - e_C\right)^2} v^2 + \frac{e_{D,f} - e_C}{\left(4e_{D,f} - e_C\right)^2} v^2, \tag{13.1}$$

$$R_C^B = \frac{4\bar{e}_{D,h}\left(\bar{e}_{D,h} - e_C\right)}{e_C\left(4\bar{e}_{D,h} - e_C\right)^2} v^2 + \frac{4e_{D,f}\left(e_{D,f} - e_C\right)}{e_C\left(4e_{D,f} - e_C\right)^2} v^2. \tag{13.2}$$

When firm D chooses a unit emission level for the foreign market different from that for the home market, the first-order condition for the profit maximization of firm D in the second stage is obtained from (4.1) and (13.1) as follows:

$$-\frac{4e_{D,f} - 7e_C}{\left(4e_{D,f} - e_C\right)^3} v^2 - F'_{D,f} = 0. \tag{14.1}$$

However, from (4.2) and (13.2), the first-order condition for firm C is given by:

$$-\sum_i \frac{4e_{D,i}\left(4e_{D,i}^2 - 3e_{D,i}e_C + 2e_C^2\right)}{e_C^2\left(4e_{D,i} - e_C\right)^3} v^2 - F_C' = 0, \quad i = h, f, \quad e_{D,h} = \bar{e}_{D,h}. \tag{14.2}$$

It is assumed that the second-order conditions are satisfied. See Appendix 3 for the details.

Based on the properties of the revenue functions, let us define the reaction functions of the unit emission levels in the Bertrand duopoly case as follows:

$$e_{D,f} = \phi_D^B(e_C),\ \phi_D'^B > 0, \tag{15.1}$$

$$e_C = \phi_C^B(\bar{e}_{D,h}, e_{D,f}), \quad \partial\phi_C^B / \partial\bar{e}_{D,h} > 0,\ \partial\phi_C^B / \partial e_{D,f} > 0. \tag{15.2}$$

Figure 3 shows these reaction functions when firm D chooses a unit emission level for the foreign market different from that for the home market. If firm D supplies the same type of dirtier product to both countries, the situation in the foreign market (the figure on the right) is the same as that in the home market (the figure on the left).

In this case, the unit emission levels of the products are strategic complements for both firms (see Appendix 3). In the Bertrand competition, as the difference in environmental quality between products increases, price competition between firms is mitigated, and the revenue of both firms increases. Therefore, a decrease in the unit emission level of the dirtier (resp. cleaner) product gives firm C (resp. firm D) an incentive to improve the environmental quality of its own product.

Based on (15.1) and (15.2), when firm D chooses the unit emission level for the product supplied to the foreign market, there is a unique and stable Nash equilibrium, i.e., $\{e_{D,f}^B, e_C^B\}$, given $\bar{e}_{D,h}$. See Appendix 2.

4. Emission Standards, Product Quality, and the Environment

In this section, we investigate the effect of a change in the emission standard set by the home government on the environmental quality of products supplied to the two markets, aggregate emissions, and net social surpluses of both countries.

4.1 Cournot Duopoly Case

First, we consider the effect on the unit emission levels of products. When firm D supplies the same type of product to both markets, which means that the unit emission level for both markets is $\bar{e}_{D,h}$, firm D does not solve the profit maximization problem, whereas firm C does. For this case, we obtain the following conditions.

Lemma 1: $0<\dfrac{de_C^C}{d\bar{e}_{D,h}}<1$ *and* $0<\dfrac{de_C^C}{d\bar{e}_{D,h}}\cdot\dfrac{\bar{e}_{D,h}}{e_C^C}<1$ *hold.*

See Appendix 4 for the proof. Lemma 1 implies that a stricter home emission standard decreases the unit emission levels of both the dirtier and the cleaner products. Moreover, the decrease in the unit emission level of the cleaner product is smaller than that of the dirtier product.

However, when firm D produces a product with a unit emission level for the foreign market different from that for the home market, the following conditions are obtained.[12]

Lemma 2: $0<\dfrac{de_C^C}{d\bar{e}_{D,h}}<1$, $0<\dfrac{de_C^C}{d\bar{e}_{D,h}}\cdot\dfrac{\bar{e}_{D,h}}{e_C^C}<1$, *and* $\dfrac{de_{D,f}^C}{d\bar{e}_{D,h}}<0$ *hold.*

See Appendix 5 for the proof. Lemma 2 implies that when the home government makes its

[12] We do not explicitly analyze the case in which firm D produces a product with a different emission level for the foreign market, and $\bar{e}_{D,f}$ is binding. This case can be analyzed in a similar way, and the results are essentially the same.

emission standard stricter, (a) the unit emission level of the cleaner product decreases, and (b) the unit emission level of the dirtier product supplied to the foreign market increases. The direct effect of this situation is shown in Figure 4.

It should be noted that when firm D supplies the same type of product to both markets, the effects of a stricter home emission standard are the same for both markets. However, when firm D supplies different types of products to each market, the effects of a stricter emission standard are different for the home and the foreign markets.

Now let us investigate the aggregate emissions. Substituting (8.1) and (8.2) into (5), the aggregate emissions level in country i is written as:

$$E_i^C = \frac{3e_{D,i} - e_{C,i}}{4e_{D,i} - e_{C,i}} \cdot v, \tag{16}$$

and the effects of changes in the unit emission levels on the aggregate emissions are given by:

$$\frac{\partial E_i^C}{\partial e_{D,i}} = \frac{e_{C,i}}{\left(4e_{D,i} - e_{C,i}\right)^2} v > 0, \quad \frac{\partial E_i^C}{\partial e_{C,i}} = -\frac{e_{D,i}}{\left(4e_{D,i} - e_{C,i}\right)^2} v < 0. \tag{17}$$

An increase in the unit emission level of the dirtier product increases the supply of the cleaner product. These effects dominate the effect of a decrease in the supply of the dirtier product. However, an increase in the unit emission level of the cleaner product (a) decreases the supply of the cleaner product, (b) decreases the unit emission level of the dirtier product, and (c) increases the supply of the dirtier product. In total, the aggregate emissions decrease.

From (17) and Lemma 1, when firm D supplies the same type of product to both markets, the effects of a stricter emission standard on the aggregate emissions are obtained:

$$\frac{dE_i^C}{d\bar{e}_{D,h}} \geq 0, \qquad i = h, f. \tag{18}$$

However, from (17) and Lemma 2, when firm D supplies different types of products to each market, the effects are given by:

$$\frac{dE_h^C}{d\bar{e}_{D,h}} \geq 0 \ , \quad \frac{dE_f^C}{d\bar{e}_{D,h}} \leq 0 \ . \tag{19}$$

Consequently, the following proposition is established.

Proposition 1: *Suppose that the firms compete with each other in a Cournot fashion. As the home emission standard becomes stricter, the home aggregate emissions decrease. However, the effect on the foreign aggregate emissions depends on whether or not firm D supplies different types of products to each market: (a) when firm D supplies the same type of product to both markets, the foreign aggregate emissions also decrease, (b) when firm D supplies different types of products to each market ($\bar{e}_{D,h} < e_{D,f}$), the foreign aggregate emissions increase.*

Now, we can derive the effects on the social net surplus. From the definition of the consumer surplus, it is easily verified that:

$$\frac{\partial CS_i^C}{\partial e_{D,i}} < 0, \ \frac{\partial CS_i^C}{\partial e_{C,i}} < 0, \qquad i = h, f. \tag{20}$$

Therefore, from Lemma 1, it is clear that $dCS_i^C \big/ d\bar{e}_{D,h} < 0 \, (i = h, f)$ holds when firm D supplies the same product to both markets. Even if firm D supplies different types of products to each market, $dCS_i^C \big/ d\bar{e}_{D,h} < 0 \ (i = h, f)$ holds, because the effect of a change in e_C dominates that of a change in $e_{D,f}$. Therefore, when the social net surplus is defined as (7), from (18) and (19), the following proposition holds.

Proposition 2: *Suppose that the firms compete with each other in a Cournot fashion. As the home emission standard becomes stricter, the home social net surplus increases, which is defined as the consumer surplus minus environmental damage. As far as firm D supplies* *the same type of product to both markets, the foreign social net surplus also increases. However, when firm D supplies different types of products to each market, the foreign social net surplus decreases if the marginal valuation of environmental damage (γ_f) is greater than a certain level, that is* $\gamma_f > \left(dCS_f^B / d\bar{e}_{D,h}\right) / \left(dE_f^B / d\bar{e}_{D,h}\right)$.

It is interesting to consider the comparison between the emission standard to maximize the home social net surplus and the world optimum, although the comparison is not our main purpose. For example, as noted in Proposition 2, when firm D supplies different types of products to each market, a stricter home emission standard may reduce the foreign social net surplus. In such a case, the standard when the home social net surplus is maximized is stricter than the world optimum.

4.2 Bertrand Duopoly Case

First, we consider the effect on the unit emission levels of products. When firm D supplies the same type of product to both markets, we obtain the following conditions.

Lemma 3: $0 < \dfrac{de_C^B}{d\bar{e}_{D,h}} < 1$ *and* $0 < \dfrac{de_C^B}{d\bar{e}_{D,h}} \cdot \dfrac{\bar{e}_{D,h}}{e_C^B} < 1$ *hold.*

See Appendix 4 for the proof. This result is the same as in the Cournot case.

However, when firm D chooses a unit emission level for the foreign market different from that for the home market, we obtain the following conditions.

Lemma 4: $0 < \dfrac{de_C^B}{d\bar{e}_{D,h}} < 1, \quad 0 < \dfrac{de_C^B}{d\bar{e}_{D,h}} \cdot \dfrac{\bar{e}_{D,h}}{e_C^B} < 1, \quad \dfrac{de_{D,f}^B}{d\bar{e}_{D,h}} > 0,$

$$0 < \frac{de_{D,f}^{B} \big/ d\bar{e}_{D,h}^{B}}{de_{C}^{B} \big/ d\bar{e}_{D,h}^{B}}, \textit{ and } \; 0 < \frac{de_{D,f}^{B} \big/ d\bar{e}_{D,h}^{B}}{de_{C}^{B} \big/ d\bar{e}_{D,h}^{B}} \cdot \frac{e_{C}^{B}}{e_{D,f}^{B}} < 1 \; \textit{ hold.}$$

See Appendix 5 for the proof. Lemma 4 implies that when the home government makes its emission standard stricter, (a) the unit emission level of the cleaner product decreases, and (b) the unit emission level of the dirtier product supplied to the foreign market also decreases. The direct effect of this situation is shown in Figure 5.

Now let us investigate the aggregate emissions. Substituting (12.1) and (12.2) into (5), the aggregate emissions level in country i is written as:

$$E_i^B = \frac{3e_{D,i}}{4e_{D,i} - e_{C,i}} \cdot v \,, i = h, f \tag{21}$$

and the effects of changes in the unit emission levels on the aggregate emissions are given by:

$$\frac{\partial E_i^B}{\partial e_{D,i}} = -\frac{3e_{C,i}}{\left(4e_{D,i} - e_{C,i}\right)^2} v < 0, \quad \frac{\partial E_i^B}{\partial e_{C,i}} = \frac{3e_{D,i}}{\left(4e_{D,i} - e_{C,i}\right)^2} v > 0 \,, \quad i = h, f \;. \tag{22}$$

Note that the directions of changes in the aggregate emissions are opposite to those in the Cournot duopoly case. Intuitively, whether or not price competition becomes more serious is an important factor. Serious competition increases the supply of both products and, accordingly, the aggregate emissions.

From (22) and Lemma 3, when firm D supplies the same type of product to both markets, the effects of a strict emission standard on the aggregate emissions are obtained:

$$\frac{dE_i^B}{d\bar{e}_{D,h}} < 0 \,, \qquad i = h, f. \tag{23}$$

However, from (22) and Lemma 4, when firm D supplies different types of products to each market, the effects are given by:

$$\frac{dE_h^B}{d\bar{e}_{D,h}} < 0\,, \frac{dE_f^B}{d\bar{e}_{D,h}} > 0\,. \tag{24}$$

Consequently, the following proposition is established.

Proposition 3: *Suppose that the firms compete with each other in a Bertrand fashion. As the home emission standard becomes stricter, the home aggregate emissions increase. However, the effect on the foreign aggregate emissions depends on whether or not firm D supplies different types of products to each market: (a) when firm D supplies the same type of product to both markets, the foreign aggregate emissions also increase, (b) when firm D supplies different types of products to each market, the foreign aggregate emissions decrease.*

Regarding the effect on the home market, Moraga-González and Padrón-Fumero (2002, Proposition 5) obtained this result. The home aggregate emissions increase as the home emission standard becomes stricter. This is because the number of consumers who buy either of two types of products increases. Then, from the environmental point of view, the home government should not set any emission standard in this case.

From the definition of consumer surplus, it is easily verified that:

$$\frac{\partial CS_i^B}{\partial e_{D,i}} < 0, \ \frac{\partial CS_i^B}{\partial e_{C,i}} < 0, \qquad i = h, f\,. \tag{25}$$

Therefore, it is clear from Lemma 3 that $dCS_i^B \big/ d\bar{e}_{D,h} < 0\,(i = h, f)$ holds when firm D supplies the same product to both markets. Even if firm D produces two types of products, $dCS_i^B \big/ d\bar{e}_{D,h} < 0\ (i = h, f)$ holds from Lemma 4. Thus, when the social net surplus is defined as (7), from (23) and (24), the following proposition holds.

Proposition 4: *Suppose that the firms compete with each other in a Bertrand fashion. When firm D supplies different types of products to each market, as the home emission standard becomes stricter, the foreign social net surplus increases. However, if the marginal valuation of environmental damage is smaller than a certain level, that is $\gamma_h > \left(dCS_h^C / d\bar{e}_{D,h}\right) / \left(dE_h^C / d\bar{e}_{D,h}\right)$, a stricter home emission standard increases the home social net surplus, which does not depend on whether firm D produces one or two types of dirtier products.*

Two points should be noted. First, similar to the Cournot duopoly case, the comparison of the optimal emission standard for the home government with the world optimum is interesting. For example, when firm D chooses a different unit emission level for the foreign market from that for the home market, it is clear from Proposition 4 that the unilateral emission standard is likely to be laxer than the world optimum.

Second, although the directions of changes are different between the Cournot and Bertrand cases, the following fact holds for both cases: when firm D produces two types of dirtier products, the effects of a stricter home emission standard on the aggregate emissions of both countries are different from each other.

5. Endogenous Determination of the Number of Types of Dirtier Products

In the previous section, the number of types of products of firm D is assumed to be exogenous. It is, however, important to consider the case in which firm D decides to produce two types of dirtier products. In this section, we focus on the difference in the social valuation of environmental damages, which is considered to be reflected in the emission standards.

If there are no emission standards in either country, firm D supplies the same type of product to both markets, because it has to pay an additional fixed cost to produce two types of products. If, however, the emission standard in one country is much stricter than that in the other country, firm D may have an incentive to supply different types of products to each market. In other words, firm D makes each type of product fit to each emission standard. Even if it has to pay an additional cost, the profit may be greater when it produces two types of dirtier products than when it supplies the same type of product to both markets because of less serious competition. Similar to the previous section, we assume that the foreign emission standard is not binding, whereas the home emission standard is binding. This implies that if firm D produces two types of products, the unit emission level of the product for the foreign market is higher than that for the home market ($\bar{e}_{D,h} < e_{D,f}$). Thus, we investigate whether or not a stricter emission standard changes firm D's decision regarding the number of types of products.

Let us begin with the case of Cournot duopoly. In this case, from (9.1), we obtain that $\partial R_D^C / \partial e_{D,f} < 0$. Because firm C supplies the same type of product to both markets, firm D has no incentive to pay an additional cost to produce another type of product. This fact immediately leads to the following proposition.

Proposition 5: *Suppose that firms compete with each other in a Cournot fashion. Then, firm* D *supplies the same type of products to both markets irrespective of the strictness of the home emission standard.*

This result is simple, but important. In the previous section, we demonstrated that whether or not firm D supplies the same type of product to both markets crucially affects the effect of a home emission standard on the aggregate emissions and the social surplus of the foreign country. Proposition 5 states that, if the number of types of products firm D

supplies is endogenously determined, and if the mode of competition is Cournot competition, the effect of a change in the home emission standard on the home country is the same as that on the foreign country.

Let us now turn to the case of Bertrand duopoly. When there is no home emission standard, $\partial R_D^B \big/ \partial e_{D,f} < 0$ holds. Even if there is a home emission standard, if it is not very strict, $\partial R_D^B \big/ \partial e_{D,f} < 0$ also holds (see Appendix 3). In this case, the same result as the case of the Cournot duopoly holds (Proposition 5). However, the stricter the home emission standard, the more likely it is that $\partial R_D^B \big/ \partial e_{D,f} > 0$ holds as long as firm D supplies the same type of product to both markets.

Let us focus on firm D's incentive to deviate from the situation in which $e_{D,f} = \bar{e}_{D,h}$. Consider the case in which $\partial R_D^B \big/ \partial e_{D,f} > 0$ holds, and let $e'_{D,f}$ denote a unit emission level that is greater than $\bar{e}_{D,h}$.

When $e_{D,f} = \bar{e}_{D,h}$, from (13.1):

$$\begin{aligned} \frac{d\pi_D^B}{d\bar{e}_{D,h}} &= \frac{\partial R_D^B}{\partial \bar{e}_{D,h}} + \frac{\partial R_D^B}{\partial e_C^B} \cdot \frac{de_C^B}{d\bar{e}_{D,h}} - F'_D \\ &= 2 \cdot \left(\frac{-4\bar{e}_{D,h} + 7e_C^B}{\left(4\bar{e}_{D,h} - e_C^B\right)^3} + \frac{-2\bar{e}_{D,h} - e_C^B}{\left(4\bar{e}_{D,h} - e_C^B\right)^3} \cdot \frac{de_C^B}{d\bar{e}_{D,h}} \right) - F'_D. \end{aligned} \tag{26}$$

Because $0 < de_C^B \big/ d\bar{e}_{D,h} < 1$, $F'_D < 0$, and $F''_D > 0$, the smaller the difference between the unit emission levels of the two firms' products, the more likely it is that $d\pi_D^B \big/ d\bar{e}_{D,h} > 0$ holds. This means that the stricter the home emission standard, the more likely it is that a small decrease in $\bar{e}_{D,h}$ decreases the profit of firm D.

However, because $\partial R_D^B \big/ \partial e_C < 0$ and $0 < de_C \big/ d\bar{e}_{D,h} < 1$, the profit of firm D increases when setting the unit emission level for the foreign market equal to $e'_{D,f}$, as the home emission standard becomes stricter. It holds for any level of $e'_{D,f}$. Thus, the following proposition holds.

Proposition 6: *Suppose that firms compete with each other in a Bertrand fashion. Then, the stricter the home emission standard, the stronger is firm D's incentive to deviate from the situation in which it supplies the same type of products to both markets.*

This result for the Bertrand case is in sharp contrast to that for the Cournot case. According to Proposition 6, when the environmental consciousness of the home country is much greater than that of the foreign country, it is likely that the unit emission level regulated by the home emission standard is lower than that of the dirtier product for the foreign market. Thus, the effect of a change in the home emission standard on the home aggregate emissions is likely to be different from that on the foreign aggregate emissions.

6. Further Discussion

6.1 Producer's Surplus and Domestic Firms

Although we have assumed to this point that firms are located outside the two consuming countries, it is possible that they are located in these countries. Therefore, the profits of firms are worth examining.

First, let us examine the profit of firm C. Whether or not firm D supplies the same type of product to both markets, firm C chooses the unit emission level of its own product to maximize its own profit given the unit emission levels of the products of firm D. Therefore, the effect of a change in the home emission standard on the profit is represented as:

$$\frac{d\pi_C^j}{d\bar{e}_{D,h}} = \frac{\partial R_C^j}{\partial \bar{e}_{D,h}} > 0 \text{, } j = B, C \text{.}$$

It is clear that the stricter the home emission standard, the smaller is the profit of firm C, when firm D supplies the same type of product. Moreover, from Lemma 4, if firms compete with each other in a Bertrand fashion, even when firms supply different types of products to each market, the profit of firm C decreases as the home emission standard becomes stricter. In this case, from (20) and (25), the effect of a stricter home emission standard on the consumer's surplus conflicts with that on the profit of firm C.

Second, let us examine the profit of firm D. From (26), we know that the effect of a change in the home emission standard on the profit is ambiguous. However, when the effect is evaluated at the unit emission level when there is no emission standard ($e_{D,0}^j$), we have that:

$$\frac{d\pi_D^j}{d\bar{e}_{D,h}} = \frac{\partial R_D^j}{\partial e_C} \cdot \frac{de_C}{d\bar{e}_{D,h}} \text{.}$$

Recall that $\partial R_D^j / \partial e_C < 0$ holds when firms compete with each other in a Bertrand fashion. In this case, both the consumer's surplus and the profit of firm D increase when the home emission standard becomes marginally stricter from $e_{D,0}^j$. This implies that Proposition 4 may hold for a country in which firm D is located, even if firms' profits are taken into consideration.

6.2 Firm C's Choice regarding the Number of Types of Cleaner Products

To this point, assuming that firm C supplies the same type of product to both markets, we have focused mainly on the types of dirtier products of firm D. This is, however, easily extended to the case in which firm C supplies different types of products to each market.

First, consider the case in which both firms determine one unit emission level for each market. When the home government makes its emission standard stricter, each firm changes the unit emission level of its own product for the home market. However, neither firm changes the unit emission levels of products supplied to the foreign market. This is because the unit emission level of the dirtier product supplied to the foreign market is not influenced by a change in the home emission standard.

Second, consider the case in which firm C determines one unit emission level for each market whereas firm D supplies only one type of product, which is supplied to both markets. In this case, a change in the home emission standard has the same effect on the unit emission levels of dirtier products supplied to both markets. Accordingly, the unit emission levels of the cleaner products supplied to both markets also change in the same way. This result is the same as the case in which each firm supplies only one type of product.

Consequently, it can be concluded that the effect of the home emission standard on the foreign market crucially depends on whether or not firm D, whose products are directly affected by emission standards, supplies different types of products to each market.

6.3 Unilateral Home Emission Standards and Foreign Environmental Damage

Finally, taking into consideration the endogenous determination of the number of types of dirtier products, we consider whether a unilateral change in the home emission standard increases the aggregate emissions in the foreign market.

According to Proposition 5, firm D never has an incentive to produce more than one type of dirtier product when firms compete in a Cournot fashion. Moreover, according to Proposition 1, only when firm D supplies different types of products to each market do the foreign aggregate emissions increase as the home emission standard becomes stricter. Consequently, in the case of Cournot duopoly, a stricter home emission standard never increases the foreign aggregate emissions.

In the case of Bertrand duopoly, when firm D supplies different types of products to each market, the foreign aggregate emissions decrease as the home emission standard becomes stricter. However, according to Proposition 3 (Moraga-González and Padrón-Fumero (2002), Proposition 5), when firm D supplies the same type of product to both markets, a stricter home emission standard increases both the home and the foreign aggregate emissions. Thus, the following case never takes place: a stricter home emission standard decreases the home aggregate emissions and increases the foreign aggregate emissions.

In summary, it can be concluded that the stricter home emission standard is not a kind of "beggar thy neighbor" policy, as far as both firms supply their products to both markets, that is, they are global firms.

However, there is a situation in which a stricter home emission standard decreases (resp. increases) the home (resp. foreign) aggregate emissions. Consider the case in which firm C is a global firm, whereas firm D is a domestic firm. This means that there is one firm that produces a dirtier product in each country, and firm D in the home (resp. foreign) country supplies its own product only to the home (resp. foreign) market. In this case, each firm D determines the unit emission level for its own product. Therefore, if firms compete in a Cournot fashion, the foreign aggregate emissions increase as the home emission standard becomes stricter.[13]

7. Concluding Remarks

We have examined the effect of a unilateral change in an emission standard on the product quality, aggregate emissions, and welfare of both domestic and foreign countries. To this end,

[13] The producer's surplus should be taken into consideration when considering the social net surplus. Thus, the effect of a stricter home emission standard is more complicated in this case than in the case in Section 4.

we employed a differentiated products model with heterogeneous consumers in terms of environmental consciousness. Moreover, we considered both Cournot and Bertrand duopoly cases.

The results we obtained are very clear: whether or not the effects of a stricter home emission standard on both the domestic and the foreign countries are the same depends on the types of products produced by the firm that supplies dirtier products (firm D). In other words, when firm D supplies different products in terms of environmental features to each market, the effects on the two countries differ from each other. This means that a unilateral change in an emission standard could be either beneficial or harmful to other countries, and that the firms' behavior regarding how many types of products they supply is crucial.

Moreover, when considering the endogenous determination of the number of types of products produced by firm D, the result in the case of Bertrand duopoly is in sharp contrast to that of Cournot duopoly. In the former case, the stricter the home emission standard, the stronger is firm D's incentive to produce two types of dirtier products. However, in the latter case, firm D keeps producing one type of dirtier product, even if the home emission standard becomes stricter.

To highlight the essence of the issue we focused on, some interesting factors were excluded from the analysis, although the results obtained in this paper are not influenced by those factors. First, the environmental criteria for cleaner products, such as environmental labeling, could also be a focus. The effects of a strict awarding rule for a 'cleaner product' on the domestic and foreign markets could also be different from each other, and may be counterintuitive. Second, the strategic behavior of both governments was not taken into consideration. It is important to verify whether or not emission standards of countries are optimal in terms of world welfare. In this respect, the situation in which a government sets its emission standard depending on the emission standards of other countries should be examined. Elucidating these effects is our future task.

Appendix 1

Given (10.1) and (10.2), the first-order properties are given by:

$$\frac{\partial R_D^C}{\partial e_{D,f}} < 0,\ \frac{\partial R_C^C}{\partial e_C} < 0,\ \frac{\partial R_D^C}{\partial e_C} > 0,\ \frac{\partial R_C^C}{\partial \overline{e}_{D,h}} > 0,\ \frac{\partial R_C^C}{\partial e_{D,f}} > 0\,. \tag{A.1}$$

Furthermore, the second-order properties are given by:

$$\frac{\partial^2 R_D^C}{\partial e_{D,f}^2} > 0,\quad \frac{\partial^2 R_C^C}{\partial e_C^2} > 0\,, \tag{A.2}$$

$$\frac{\partial^2 R_D^C}{\partial e_{D,f}\partial e_C} < 0,\ \frac{\partial^2 R_C^C}{\partial e_C \partial e_{D,f}} > 0,\ \frac{\partial^2 R_C^C}{\partial e_C \partial \overline{e}_{D,h}} > 0\,. \tag{A.3}$$

From (A.2), since it holds that the revenue functions are not concave, the cost functions should be sufficiently convex to ensure that the second-order conditions hold. (A.3) implies that the unit emission levels of the products are strategic substitutes (resp. complements) for firm D (resp. firm C) in the Cournot duopoly case.

Appendix 2

The determinant of the matrix can be generally expressed as:

$$\Delta^k = \frac{\partial^2 \pi_D^j}{\partial e_D^2}\frac{\partial^2 \pi_C^j}{\partial e_C^2} - \frac{\partial^2 \pi_D^j}{\partial e_{D,f}\partial e_C}\frac{\partial^2 \pi_C^j}{\partial e_C \partial e_{D,f}},\qquad j = C, B \tag{A.4}$$

Furthermore, from (11.1), (11.2), (15.1) and (15.2), the following equations hold:

$$e_{D,f}\frac{\partial^2 R_D^k}{\partial e_{D,f}^2} + e_C\frac{\partial^2 R_D^k}{\partial e_{D,f}\partial e_C} = -2F'_{D,f} \tag{A.5.1}$$

$$e_C\frac{\partial^2 R_C^k}{\partial e_C^2} + e_{D,f}\frac{\partial^2 R_C^k}{\partial e_C \partial e_{D,f}} + \overline{e}_{D,h}\frac{\partial^2 R_C^k}{\partial e_C \partial \overline{e}_{D,h}} = -2F'_C \tag{A.5.2}$$

Substituting (A.5.1) and (A.5.2) into (A.4), we obtain that

$$\Delta^j = \frac{e_{D,f}}{e_C}\frac{\partial^2 R_C^j}{\partial e_C \partial e_{D,f}}\left(-\frac{F'_{D,f}}{e_{D,f}}\right)(\eta_{D,f}-2) + \frac{e_C}{e_{D,f}}\frac{\partial^2 R_D^j}{\partial e_{D,f}\partial e_C}\left(-\frac{F'_C}{e_C}\right)(\eta_C - 2)$$
$$+\left(-\frac{F'_{D,f}}{e_{D,f}}\right)(\eta_{D,f}-2)\left(-\frac{F'_C}{e_C}\right)(\eta_C-2) \qquad \text{(A.6)}$$
$$+\frac{\bar{e}_{D,h}}{e_C}\frac{\partial^2 R_C^j}{\partial e_C \partial \bar{e}_{D,h}}\cdot\left\{\frac{e_C}{e_{D,f}}\frac{\partial^2 R_D^j}{\partial e_{D,f}\partial e_C} + \left(-\frac{F'_{D,f}}{e_{D,f}}\right)(\eta_{D,f}-2)\right\},$$

where $\eta_C \equiv e_C F''_C/(-F'_C)$, and $\eta_{D,f} \equiv e_{D,f}F''_{D,f}/(-F'_{D,f})$. From (3.1) and (3.2), both of them are equal to $\varepsilon + 1(>2)$.

In the Bertrand duopoly case, since all cross partial derivatives are positive (See Appendix 3), the sign of the determinant is positive. Thus, the stability condition is satisfied. On the other hand, in the Cournot duopoly case, $\partial^2 R_D^C / \partial e_{D,f}\partial e_C < 0$. However, if $\partial^2 \pi_D / \partial e_{D,f}^2 < 0$ and $\partial^2 \pi_C / \partial e_C^2 < 0$ holds, it is clear from (A.4) that the sign of the determinant is positive. This fact is also verified from (A.6). If $\partial^2 \pi_D / \partial e_{D,f}^2 < 0$ holds, the absolute value of the third term in (A.6) is greater than that of the second term. Thus, the stability condition is satisfied.

Appendix 3

Given (14.1) and (14.2), the first-order properties are given by:

$$\frac{\partial R_D^B}{\partial e_{D,f}} \geq (<) 0 \Leftrightarrow \frac{7}{4}e_C \geq (<) e_{D,f} \quad , \frac{\partial R_C^B}{\partial e_C} < 0,\ \frac{\partial R_D^B}{\partial e_C} < 0,\ \frac{\partial R_C^B}{\partial \bar{e}_{D,h}} > 0,\ \frac{\partial R_C^B}{\partial e_{D,f}} > 0. \qquad \text{(A.7)}$$

We assume the existence of an interior solution such that $7e_C/4 < e_{D,f}$ when firm D chooses a unit emission level for the foreign market different from that for the home market. Furthermore, the second-order properties are given by:

$$\frac{\partial^2 R_D^B}{\partial e_{D,f}^2} \geq (<) 0 \Leftrightarrow e_{D,f} \geq (<) \frac{5}{2} e_C, \quad \frac{\partial^2 R_C^B}{\partial e_C^2} > 0, \tag{A.8}$$

$$\frac{\partial^2 R_D^B}{\partial e_{D,f} \partial e_C} > 0, \ \frac{\partial^2 R_C^B}{\partial e_C \partial e_{D,f}} > 0, \ \frac{\partial^2 R_C^B}{\partial e_C \partial \bar{e}_{D,h}} > 0. \tag{A.9}$$

From (A.7), since it holds that the revenue functions are not necessarily concave, the cost functions should be sufficiently convex to ensure that the second-order conditions hold. (A.8) implies that the unit emission levels of the products are strategic complements for both firms in the Bertrand duopoly case.

Appendix 4

In this Appendix, the same results hold for both modes of competition, we abbreviate superscripts B and C. When $e_{D,f} = \bar{e}_{D,h}$,

$$\frac{de_C}{d\bar{e}_{D,h}} = -\frac{\dfrac{\partial^2 \pi_C}{\partial e_C \partial \bar{e}_{D,h}}}{\dfrac{\partial^2 \pi_C}{\partial e_C^2}} \tag{A.10}$$

From (A.3), when the second order conditions are satisfied, (A.10) is positive. In this case, (A.5.2) can be rewritten as:

$$e_C \frac{\partial^2 R_C}{\partial e_C^2} + \bar{e}_{D,h} \frac{\partial^2 R_C}{\partial e_C \partial \bar{e}_{D,h}} = -2F_C'. \tag{A.5.2)'}$$

Thus,

$$\frac{de_C}{d\bar{e}_{D,h}} = \frac{\dfrac{\partial^2 R_C}{\partial e_C \partial \bar{e}_{D,h}}}{\dfrac{\bar{e}_{D,h}}{e_C} \dfrac{\partial^2 R_C}{\partial e_C \partial \bar{e}_{D,h}} - \dfrac{F_C'}{e_C} \cdot (\eta_C - 2)} \tag{A.11}$$

Since $\eta_C > 2$ and $\bar{e}_{D,h} > e_C$, Lemmas 1 and 3 hold.

Appendix 5

We basically abbreviate superscripts B and C in this Appendix. The effect of a change in the home emission standard on the unit emission levels are obtained as follows:

$$\frac{de_{D,f}}{d\bar{e}_{D,h}} = \frac{\dfrac{\partial^2 \pi_C}{\partial e_C \partial \bar{e}_{D,h}} \dfrac{\partial^2 \pi_D}{\partial e_{D,f} \partial e_C}}{\dfrac{\partial^2 \pi_D}{\partial e_{D,f}^2} \dfrac{\partial^2 \pi_C}{\partial e_C^2} - \dfrac{\partial^2 \pi_D}{\partial e_{D,f} \partial e_C} \dfrac{\partial^2 \pi_C}{\partial e_C \partial e_{D,f}}} \tag{A.12.1}$$

$$\frac{de_C}{d\bar{e}_{D,h}} = \frac{-\dfrac{\partial^2 \pi_C}{\partial e_C \partial \bar{e}_{D,h}} \dfrac{\partial^2 \pi_D}{\partial e_{D,f}^2}}{\dfrac{\partial^2 \pi_D}{\partial e_{D,f}^2} \dfrac{\partial^2 \pi_C}{\partial e_C^2} - \dfrac{\partial^2 \pi_D}{\partial e_{D,f} \partial e_C} \dfrac{\partial^2 \pi_C}{\partial e_C \partial e_{D,f}}} \tag{A.12.2}$$

From (A.3) and (A.9), (A.12.1) is negative (resp. positive) in the Cournot (resp. Bertrand) duopoly case. (A.12.2) is positive regardless of the mode of competition. Thus,

The numerator of (A.12.2) is

$$-\frac{\partial^2 \pi_C}{\partial e_C \partial \bar{e}_{D,h}} \frac{\partial^2 \pi_D}{\partial e_{D,f}^2} = \left(\frac{e_C}{e_{D,f}} \frac{\partial^2 R_D}{\partial e_{D,f} \partial e_C} + \frac{2F'_{D,f}}{e_{D,f}} + F''_{D,f} \right) \frac{\partial^2 R_C}{\partial e_C \partial \bar{e}_{D,h}} .$$

If $\partial^2 \pi_D / \partial e_{D,f}^2 < 0$ holds, from (A.6), Lemma 2 holds.

From (A.12.1) and (A.12.2), it holds that

$$\frac{de_{D,f}}{d\bar{e}_{D,h}} \Bigg/ \frac{de_C}{d\bar{e}_{D,h}} = -\frac{\partial^2 \pi_D}{\partial e_{D,f} \partial e_C} \Bigg/ \frac{\partial^2 \pi_D}{\partial e_{D,f}^2} \tag{A.13}$$

In the case of Bertrand competition, if $\partial^2 \pi_D / \partial e_{D,f}^2 < 0$ holds, (A.13) is positive. Taking (A.5.1) and $\eta_{D.f} > 2$ into consideration, Lemma 4 holds.

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Figure 1. Framework of the Model

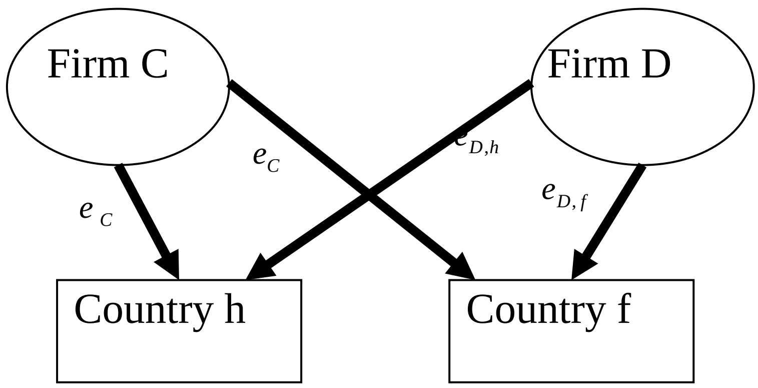

Figure 2. Reaction Functions in the case of Cournot duopoly

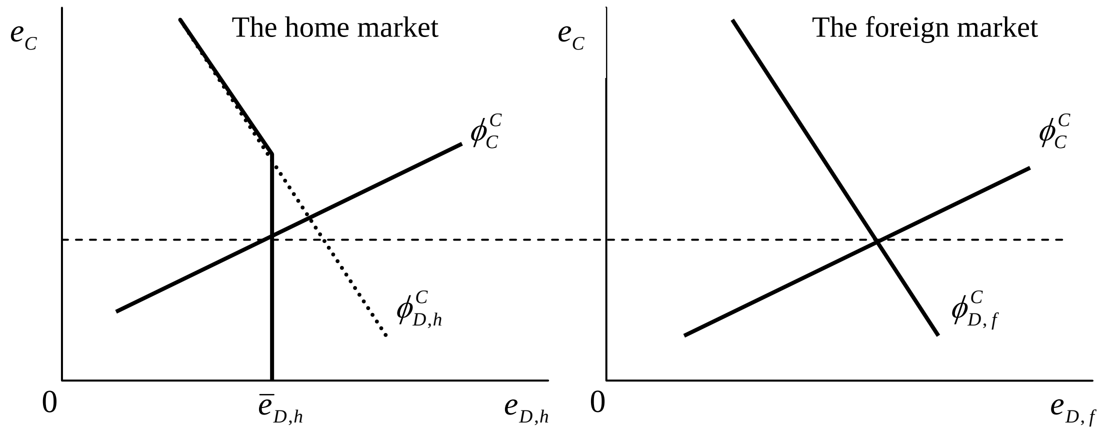

Figure 3. Reaction Functions in the case of Bertrand duopoly

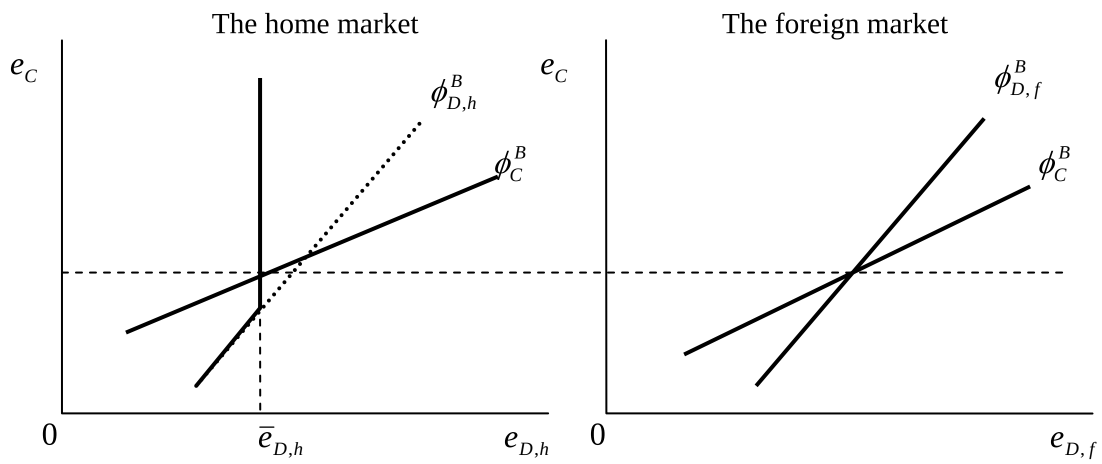

Figure 4. The effect of a stricter home emission standard

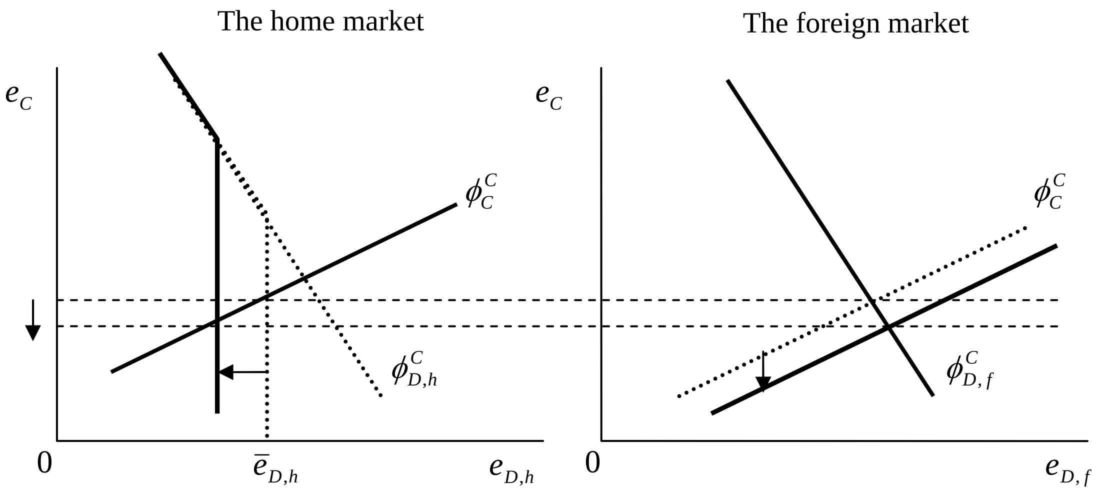

Figure 5. The effect of a stricter home emission standard